TECHNICAL NOTE No. 194

MEASUREMENT OF TEMPERATURE AND HUMIDITY

SPECIFICATION, CONSTRUCTION, PROPERTIES AND USE OF THE WMO REFERENCE PSYCHROMETER

by

Russell G. Wylie and Theo Lalas

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WMO-No. 759

Secretariat of the World Meteorological Organization - Geneva - Switzerland
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* On 31 December 1991
A reference psychrometer constructed by CSIRO. In this particular design the specified outer shield is concealed by a further shield of box-like form. Mercury-in-glass thermometers are shielded from extraneous radiation by hemi-cylindrical shields which extend to the left. The connection to the fan is at the rear, the tubes connecting to the manometer which indicates the airspeed are below, and part of the radiation shield which surrounds the water reservoir is seen at the extreme right. The instrument has usually been used with electrical thermometers substituted for the mercury-in-glass thermometers.
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FOREWORD

The WMO Reference Psychrometer has been developed primarily to provide a convenient means whereby the performance of meteorological humidity instrumentation used at the earth's surface can be determined in terms of true humidity values. The Working Group on Hygrometry established in 1961 by the Commission for Instruments and Methods of Observation (CIMO) was assigned the task of recommending an "interim portable reference hygrometer" and arranging "through the President of the Commission for the hygrometer to be tested in one or more national laboratories".

Meeting in Washington on 22 May 1963, that working group decided to recommend that the reference hygrometer should be a psychrometer with standardized forced ventilation, and that its use should be restricted to conditions such that the wet-element temperature is not below 0°C. In due course, WMO accepted these recommendations.

It was clear that the reference psychrometer would have to operate accurately in the field, in sunlight and while changes in the atmospheric conditions were occurring, and it was found that no suitable instrument was available commercially. Further, at the time, the physical processes which occur in a psychrometer were not properly understood, and good agreement, both in relative and absolute terms, between the observed and calculated characteristics of psychrometers had yet to be achieved.

The Australian National Standards Laboratory (now the CSIRO Division of Applied Physics) was already interested in the basics of psychrometry, and in 1965 decided to institute a theoretical and experimental basic study of the subject and, in view of the requirement recognised by WMO, to develop a suitable reference psychrometer in parallel with the study. The results of the study and the development were summarized progressively in the final reports of CIMO working groups and rapporteurs from 1969 to 1981.

At its meeting in Hamburg in August 1977, CIMO recommended that WMO adopt the reference psychrometer as the reference standard for meteorological humidity measurements at the earth's surface such that the wet-element temperature is not below 0°C. The recommendation was adopted by the thirtyeth session of the Executive Committee in 1978. At its eighth session in 1981, CIMO further recommended that the reference psychrometer also be adopted as the reference instrument for determining the relationship between the air temperature measured by conventional surface instruments and the true air temperature. This recommendation was adopted by the thirty-fourth session of the Executive Committee at its meeting in 1982.

In 1977 CIMO assigned to the rapporteur the task of preparing an integrated technical report on the reference psychrometer, and it was agreed that it should be produced by the Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia, and that it should be distributed both by CSIRO and WMO. This arrangement recognised both the interests of WMO and those of CSIRO, in whose laboratories the instrument had been developed. It also recognised that the psychrometer has applications as a reference standard in other areas as well as meteorology. That report was issued as the "The WMO Reference Psychrometer", Russell G Wylie and Theo Lallas; 58 pp; CSIRO, distributed by CSIRO and WMO, 1981.

CIMO, at its ninth session in 1985, requested that the specification of the reference psychrometer, including engineering drawings, be published by WMO after the receipt of further material from Australia. The present publication is the result. It is based on the 1981 report, with some minor revisions and with the addition of drawings which may be used to construct a particular realization of the specification.
Dr Wylie, the principal author of this publication, has been associated with the development of the reference psychrometer since its beginnings in 1961, as member and chairman of successive CIMO working groups, and as rapporteur to CIMO. His fundamental research on psychrometry, which has elucidated the wet-element processes and reconciled the theoretical and experimental values of the psychrometer coefficient by establishing the true value of the latter, underlies the present publication. With gratitude and respect we acknowledge his important contributions to the science of meteorological measurements.

It is with regret that we record the death of Theo Lalas on 19 February 1985. May this report serve as a record of our thanks for his contribution to the development of the WMO Reference Psychrometer.

G.O.P. Obasi
Secretary General
CHAPTER 1

INTRODUCTION

1.1 Outline

The main purpose of this publication is to serve as a specification for the design and construction of the WMO Reference Psychrometer and to describe how it must be operated in the laboratory and in the field to obtain measurements of air temperature and humidity with very high accuracy. It also gives an account of the principles of the psychrometer. It summarizes the relevant findings of recent basic studies, which have resulted in the achievement of very close agreement between the observed behaviour of psychrometers and the behaviour predicted by a priori theory and also have led to a large increase in the absolute accuracy of psychrometric water vapour measurement. The application of these findings to the general practice of operational psychrometry is desirable.

The Basic Specification of the reference psychrometer, which is given in Chapter 5, is in accordance with the underlying principles set out in Chapters 2, 3 and 4. The Practical Specification in Chapter 6 expresses requirements to be observed in preparing detailed manufacturing specifications and drawings. A set of working drawings which represent the particular practical realization adopted by the CSIRO Division of Applied Physics is provided in reduced form at the end of this publication. Any psychrometer which complies with the Practical Specification is a WMO Reference Psychrometer.

The design of the reference psychrometer is based on research which has shown that the psychrometer coefficient is fully calculable for wet elements with laminar boundary-layer flows, and that the psychrometer coefficient for a practical wet element is closely related to the coefficient for such a flow and so is calculable. The calculated value has been confirmed experimentally with high accuracy, and humidity measurements made with the reference psychrometer have very small uncertainties (discussed in Chapter 10).

The psychrometer itself and its ancillary systems for the measurement of temperature and airspeed have been designed for practical operation in the field, but to ensure accuracy its use has to be closely supervised by staff who understand the basis of its design and have a good appreciation of careful laboratory work. Properly used, it gives values of humidity of lower uncertainty than those given by any other hygrometer.

Some features of the reference psychrometer are that:

- It has been developed to serve as a reference instrument against which other systems for measuring temperature and humidity may be tested. It is not intended for continuous use in routine meteorological operations.

- It is to be used as a free-standing instrument, and not within a screen or shelter. When it is compared with sensors which are mounted in a screen, the differences between the reference psychrometer and the instruments under test include the effect of the screen on the measurements made by the latter. (If the reference psychrometer itself were installed inside a screen, it would measure the temperature and humidity within the screen, but these would not in general be the same as the true temperature and humidity of the air outside).

- It is so designed that it will perform accurately in direct sunlight, but it must not be used with direct sunlight incident on its air inlet.

- It is not operable when the wet-element temperature is below 0°C.

- It is suitable for operation with electrical thermometers, which may be connected to recording instruments.
When used within the laboratory in, for example, an atmosphere of 50% relative humidity at 20°C, it is capable of measuring the humidity with an uncertainty of ±0.3% relative humidity and the temperature with an uncertainty of ±0.03°C. For similar conditions in the field, where it may be exposed to direct sunlight, it is capable of measuring the humidity with an uncertainty of ±0.4% relative humidity and the temperature with an uncertainty of ±0.04°C.

Some aspects of the management of the reference psychrometer are that:

- Simple tests specified or described in Chapter 8 and Section 11.2 allow the conformity, or continuation of the conformity, of a WMO Reference Psychrometer with the present specification to be checked.

- One test ensures that no significant error in the observed wet-element temperature is caused by the conduction of heat along the element from its ends or supports.

- The surface of the wet element must be clean. Procedures are specified for the avoidance or removal of organic films such as can arise from contact with the hands.

- When the instrument is used, the airspeed has to be set according to the approximate indications of a U-tube manometer which is part of the instrument.

- Some restrictions exist on the orientation of the axis of the instrument with respect to the direction of the sun and the wind.

- The discharge of air from the instrument has to be some distance downwind from the instrument, so that no recirculation occurs.

When a broad general specification for the reference psychrometer was being established about 25 years ago, it was considered desirable to provide for mercury-in-glass thermometry as an alternative to electrical thermometry. However, electrical resistance thermometry has now become the usual choice where temperature must be measured accurately, and it will be the more appropriate for the reference psychrometer in the great majority of cases. The present text provides for both alternatives, but the drawings at the end of this publication show only the details for electrical thermometry.

1.2 The Purposes, General Nature, and Accuracy of the Reference Psychrometer

Meteorological humidity measurements must be made in the field, where steps must be taken to reduce the effects of radiation, especially direct sunlight. Consequently, the hygrometers used, as well as any associated thermometers, are usually installed in meteorological screens. These are only partially effective.

The temperature and uniformity of the temperature of the air moving through a screen are to some degree affected by the temperature of the exterior surfaces. Also, the thermal radiation at a point within a screen in general neither corresponds accurately to the air temperature at the point nor is isotropic. The magnitude of these effects is, of course, governed not only by the external radiation but also by the wind. Further, for the commonest type of field hygrometer, namely the naturally ventilated psychrometer, the air movement within the screen has a direct effect.

By using radiation shields of advanced design along with forced ventilation, the effects of the radiation can be reduced considerably. The airspeed dependence of the behaviour of the hygrometer can be reduced by using a psychrometer with forced ventilation, or a hygrometer like a Dewcel or an automatic dew-point hygrometer which is not particularly sensitive to air movement. Installations which embody such features are in use in some countries, at least experimentally. They are, however, more complex than the classical type, and have their own limitations. Moreover, they are likely still to involve significant radiation errors.
While the intrinsic characteristics of field hygrometers can be determined by removing them to the laboratory for comparison with a reference-standard hygrometer or calibration with a humidity generator, the overall performance of the field installation can be determined only by extensive tests in the field. For such tests an instrument is required which gives the true humidity and temperature of the natural airstream incident on the installation. The WMO Reference Psychrometer has been developed for the purpose. It has the performance necessary to test even the most advanced types of installations.

Essentially, there are three reasons for choosing a psychrometer for the reference instrument:

- A psychrometer is simple and reliable, and even with modest maintenance will not change its characteristics significantly over a long period.

- As the hygrometers in field installations are commonly psychrometers, the choice of a psychrometer for the reference instrument means that instruments of a somewhat similar nature are compared. The wet- and dry-element temperatures can be compared individually, and even the effects of atmospheric fluctuations on those temperatures are likely to be at least somewhat similar.

- When a psychrometer is suitably designed, and certain precautions are taken in its use, its absolute accuracy can exceed that of any other type of hygrometer, including the dew-point hygrometer.

Only the first two of these reasons were known in 1963 when the decision to adopt a psychrometer was made. The third has become known from recent studies at the CSIRO Division of Applied Physics (Wylie, 1979; Wylie and Lalas, 1981b; Wylie and Lalas, 1985).

It is not implied that field hygrometers need not be calibrated in the laboratory. Indeed, they often have shortcomings which should be eliminated or calibrated-out before the more difficult aspect of the errors due to conditions in the field is considered. Therefore both laboratory and field tests are generally necessary.

For many purposes other than meteorological observation, accurate measurements of atmospheric humidity must be made in the laboratory. Such measurements are needed particularly where atmospheres are controlled for conditioning moisture-sensitive materials which are to be tested. The reference psychrometer is a suitable reference standard for measurements in conditioning rooms. It may be used either to check the atmospheres directly or to test the monitoring instruments, which may be calibrated in situ. More generally, the psychrometer may be used in the laboratory for the calibration of any type of hygrometer under whatever atmospheric conditions can be established. In such applications, the errors due to radiation extraneous to the instrument are likely to be entirely negligible, and the effects of atmospheric fluctuations much smaller and much more predictable than in the field.

If the psychrometer is used in the laboratory, and the parameters which it involves, and also the measurements made of the wet- and dry-element temperatures, have the maximum uncertainties allowed by the specification given below, then for standard atmospheric pressure, a temperature of 20°C and a nominal relative humidity of 50%, the absolute uncertainty in the derived humidity is ±0.30% relative humidity. However, if the wet-element overall diameter, the airspeed and the wet-and dry-element temperatures are measured more accurately than specified, this uncertainty can be reduced to as little as ±0.12% relative humidity. For field applications the uncertainty is greater, and the degree to which it can be reduced is less. In general, the uncertainty in the relative humidity decreases with increasing temperature and increasing relative humidity.
CHAPTER 1

The reference psychrometer differs from conventional psychrometers in a number of respects, some not apparent at first sight, but its high performance is associated mainly with the following innovations and new knowledge:

- Features which ensure that the conduction of heat into the wet element from its ends and supports, and along the thermometer stem or leads, is negligible.
- The establishment of a well defined radiation environment for the wet element.
- The achievement of a wet surface free from significant organic films.
- The knowledge that, with the attainment of the preceding features, the psychrometer coefficient $A$ for a well designed psychrometer is reproducible from one individual instrument to another within 0.1%.
- A knowledge of the absolute value of the psychrometer coefficient $A$ for the reference psychrometer with an uncertainty at least ten times smaller than that of the values used for conventional psychrometers.

It may be noted that one of the findings in the recent studies referred to has been that, when conventional types of psychrometers such as the whirling psychrometer and the Assmann psychrometer are well designed and are operated with clean wet-element surfaces, the value of $A$ which must be used with them to obtain true values of humidity is not approximately $6.7 \times 10^{-4} \text{ K}^{-1}$ as generally accepted, but approximately $6.2 \times 10^{-4} \text{ K}^{-1}$. For commonly occurring atmospheric conditions, the difference can correspond to an error of 2% relative humidity.

The reason for the bias in the accepted values is not certain. However, it has been found that if an organic film originating from direct or indirect contact with the hands is present on the water surface, the value of $A$ can be increased by as much as 10%. As a film results in the value of $A$ being indefinite, the importance of working with an effectively clean surface is clear. The reference psychrometer is operated with such a surface, and simple techniques by which an effectively clean surface can be achieved and tested for are described below. The value of $A$ for the instrument varies slightly with atmospheric conditions, but in the range of conditions given in the following paragraph does not depart much from $6.2 \times 10^{-4} \text{ K}^{-1}$.

The range of conditions within which a psychrometer is to be used has a bearing not only on the design of the instrument but on the tables or formulation which must be given for use with it. The reference psychrometer and its associated tables and formulation have been developed for use within the following limits:

- Atmospheric pressure: 650 to 1100 hPa
- Air temperature: 0 to 50°C
- Wet-element temperature: 0 to 35°C.

Apart from excluding conditions for which the wet-element temperature is below 0°C, these limits embrace all but the most extreme conditions which occur at the earth's surface.

In the following, no attempt is made to report the development of the reference psychrometer in its historical sequence. The justification for most of the statements made about psychrometers with transversely ventilated cylindrical wet elements is to be found in the papers referred to above. To avoid referring repeatedly to those papers, we will refer simply to "the recent studies."
The notation in this publication differs from that in the research papers referred to which use essentially the international notation of physical chemistry. It also differs slightly from that used in other WMO publications in that it omits the subscript $v$ attached to some symbols to denote water vapour, and also omits the prime attached to the symbol $e$ for the vapour pressure to denote that the vapour is in the presence of air. Thus the vapour partial pressure is denoted by $e$, not $e'$. The reason for these departures from the usual WMO practice is that in this particular text they do not cause ambiguity, and they avoid complexity in the equations.

All uncertainties given in the publication are at the 95% confidence level. The 95% confidence limits associated with the measured value of a parameter should both lie between the tolerance limits defined by the specified value of the parameter and the associated specified tolerance. There is then a probability of 95% or more that the true value of the parameter lies between the tolerance limits.
CHAPTER 2

FUNDAMENTAL ASPECTS

2.1 The Psychrometer Equation and the Psychrometer Coefficient $A$

It is an intrinsic property of a psychrometric wet element that, even if heat conduction within the element is negligible, the surface temperature of the element is practically uniform. We may therefore speak of the wet-element temperature, and define the psychrometer coefficient $A$ precisely by writing the psychrometer equation in the form

$$(x_w - x) = A(T - T_w),$$  \hspace{1cm} (1)$$

where $T$ is the temperature and $x$ the vapour mole fraction of the airstream, and $x_w$ is the saturation vapour mole fraction corresponding to the wet-element temperature $T_w$.

The saturation mole fraction $x_w$ is given by

$$x_w = f_w \frac{e_w}{p},$$ \hspace{1cm} (2)$$

where $e_w$ is the saturation pressure of pure water vapour at $T_w$, $p$ is atmospheric pressure, and $f_w$ is the enhancement factor defined by Goff and Gratch (Goff, 1949).

As $T$ and $T_w$ are observable, and $p$ is observable or otherwise obtainable, then, provided the appropriate value of $A$ is known, equations (1) and (2) allow the mole fraction $x$ of water vapour in the atmosphere to be determined. Multiplying $x$ by $p$ we get the partial pressure $e$ of the water vapour in the atmosphere, and evaluating $100x/x_s$, where $x_s$ is the saturation mole fraction corresponding to the air temperature $T$, we get the percentage relative humidity $U$.

The saturation pressure of pure water vapour has been given by Wexler (1976). Accurate values of $f_w$ for various temperatures and atmospheric pressures, which differ slightly from those given by Goff and Gratch, are given in Table 1. These have been calculated using values of the interaction coefficient $B_{aw}$ obtained by Hyland and Wexler (1973) and Wylie and Fisher (1974).

It may be noted that the derived humidity is not particularly sensitive to the value adopted for $A$. For example, for standard atmospheric pressure, a temperature of 20°C and a relative humidity of 50%, a decrease of 10% in $A$ increases the derived relative humidity only to 51.7%.

In the present range of conditions (Chapter 1), the value of $A$ is only slightly dependent on $T$, $T_w$, and $p$. Neither does $A$ vary greatly with the design of the wet element or with the airstream.

2.2 The Radiation and $\alpha$ Factors

By deriving equation (1) from basic heat- and mass-transfer relationships, we obtain an expression for $A$ as the product of three factors:

$$A = A_e(1 + \frac{h_r}{h_e})(1 + \frac{k_r}{k_e}),$$ \hspace{1cm} (3)$$

where $h_e$ and $k_e$ are respectively the mean surface convective heat- and vapour-transfer coefficients, $h_r$ is the radiative heat-transfer coefficient, $k_e$ is the mass-transfer coefficient which represents the surface resistance to evaporation associated with the evaporation (or condensation) coefficient $\alpha$, and $A_e$ may
be called the convective psychrometer coefficient. The first and second bracketed factors in equation (3) are respectively the radiation and $\alpha$ factors. For the hypothetical system in which neither the radiative heat transfer nor the $\alpha$ resistance occur, ie for the purely convective system, the radiation and $\alpha$ factors are both unity, and the psychrometer coefficient is simply $A_c$.

For the reference psychrometer, the radiation factor ranges from approximately 1.04 for the lowest temperatures and humidities at a pressure of 1100 hPa (Chapter 1), to approximately 1.09 for the highest temperatures and humidities at a pressure of 650 hPa. The corresponding range of the $\alpha$ factor is from approximately 1.004 to approximately 1.007.

The dependence of $A$ on the airspeed and the size of the wet element arises practically entirely from the radiation and $\alpha$ factors. For a few types of wet elements, this dependence can be derived from the recent studies. The results agree with the predictions of equation (3) within the estimated uncertainty of the comparison, which for the cylinder in a transverse airstream corresponds to 0.3% in $A$.

2.3 The Convective and Basic Psychrometer Coefficients $A_c$ and $B_c$

It is convenient to define a basic psychrometer coefficient $B_c$ by writing

$$B_c = \frac{A_c}{(1 - x_w)} .$$

For the usual conditions of operation of psychrometers, the values of $A_c$ and $B_c$ are practically independent of the airspeed and the size of the wet element, but depend slightly on the type of element. For example, for the cylinder in a transverse stream the values are approximately 0.7% greater than for the classical flat-plate system. Further they depend only slightly on $T$ at constant $T_w$. However, they have an experimentally observable dependence on $T_w$.

In the meteorological range (at the earth's surface) the dependence of $B_c$ on $T_w$ is approximately linear, while that of $A_c$ has a very shallow maximum of $A_c$ at a temperature ($T_w$) which for standard atmospheric pressure is approximately 10°C.

$A_c$ and $B_c$ also depend on the type of wet covering used, but, provided the covering is of cotton, the dependence is slight. For example, for a transversely ventilated cylinder the values are only 0.2% greater for a cotton-yarn wound surface, and 0.4% greater for a cotton-sleeve covered surface, than for a smooth cylinder of water.

For a few types of wet elements, including the transversely ventilated cylinder, absolute values of $A_c$ (or $B_c$) can be derived from experimental results obtained in recent studies. They agree with values derived from a priori theory within the estimated uncertainty of the comparison, which is 1%. For the transversely ventilated cylinder, the experimental results are for $T_w$ from 0 to 20°C. When a small adjustment, well within the uncertainty involved, is made to the value originally adopted in the recent studies for the diffusivity of water vapour in air, slightly affecting its temperature dependence, the a priori theory reproduces all the experimental results very accurately. The theory may then be used with confidence to derive the quantitative properties of that system for a wide range of conditions. In particular, the value of $A$ may be obtained with an uncertainty of only 0.4%.
Table 1. Values of the Factor $f_w$ by which the Saturation Vapour Pressure of Water is Increased by the Presence of Air

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CHAPTER 3

PRINCIPLES FOLLOWED IN DESIGNING AND SPECIFYING THE PSYCHROMETER

Some broad general principles have been observed in choosing the type of psychrometer system, the design, and the way in which the specification is given.

3.1 The Type of Psychrometer System

It has been considered that the system should

(i) Be easy to realize in a practical form, and, in particular, be compatible with readily available types of thermometers and wet coverings.

(ii) Involve a minimum number of significant parameters.

(iii) Lead to a practical system the properties of which are not unduly sensitive to the parameters.

(iv) Be such that the practical system can be amenable to simple tests to verify that it is practically equivalent to the ideal system.

It is shown below that these principles lead decisively to the choice of the cylinder in a transverse airstream.

3.2 The Design

It has been considered that the design should

(i) Be as simple as is consistent with the desired performance.

(ii) Preserve the possibility allowed by the choice of system that the psychrometer can easily be tested for practical equivalence to the ideal system.

(iii) Not necessitate unduly expensive or unduly sophisticated components, eg for measurement of the temperatures.

(iv) Be determined by the specification to a degree of detail just sufficient to ensure that no difficult decisions are left to the maker.

3.3 The Specification

The specification is given at two levels. Firstly, a basic specification is given which defines the ideal system on which the design is based. It states the type of system, and specifies the small number of parameters which must be given to fix the value of the psychrometer coefficient $A$.

Secondly, a practical specification is given which specifies those structural features which have a bearing on the value of $A$, or on the magnitudes of various errors. This longer specification in effect reiterates the values of the parameters given in the basic specification but gives tolerances for them. It takes account of the effects of heat conduction to the wet element from adjacent parts, of extraneous radiation, and of other possible sources of error, and it specifies the critical parts of the instrument, giving dimensions and tolerances. However, it does not include details which may be left to the maker.
The basic and practical specifications are given in Chapters 5 and 6 respectively. Reduced size copies of detailed manufacturing drawings are included at the end of this report for potential users who wish to adopt an existing realization of the reference psychrometer without undertaking local design work for the non-critical parts of the instrument. These drawings represent the Australian version of the practical realization of the reference psychrometer.
CHAPTER 4

CHOICE OF SYSTEM

4.1 The Radiation Regime

By the psychrometer system we mean not only the shape of the wet element and its orientation with respect to the airstream (we consider only a uniform laminar free stream), but also the radiation conditions. We will consider the latter first, as the same radiation conditions would be chosen regardless of the former aspects.

The great majority of psychrometers which have forced ventilation and have their wet elements exposed to blackbody radiation corresponding to the dry-element temperature have a radiation factor (equation (3)) in the range 1.03 to 1.15. The \( \alpha \) factor, generally overlooked by earlier workers, is closer to unity, and the larger the radiation factor the greater is the dependence of the psychrometer coefficient \( A \) on the airstream. Therefore, the idea is sometimes encountered that, to make \( A \) more nearly constant, the radiative heat transfer should be reduced as far as possible by a polished shield. The old idea that elimination of the radiative heat transfer would give a value of \( A \) that corresponds to \( T_w \) being the temperature of adiabatic saturation has, however, long since been shown to be incorrect.

One type of psychrometer which includes an internally polished radiation shield is the Assmann psychrometer. The objection to the polished shield for a precise instrument lies simply in the fact that while it might reduce the radiative heat transfer by as much as a factor of four it cannot eliminate it, and the residual transfer is likely still to contribute 2 to 7% to \( A \). This contribution is, unfortunately, dependent not only on the wet-element dimensions and the airstream, but also on the dimensions and reflectance of the shield. The result is that the value of \( A \) is not very uniform from one practical instrument to another, and subject to unnecessary uncertainty.

To establish a well defined situation with any degree of facility, the wet element, which in practice has an emissivity (or absorptance) close to 100%, must be exposed to blackbody radiation corresponding to the dry-element temperature. For work in the laboratory, such an exposure can be approximated simply by dispensing with a radiation shield. The wet element is then situated in an approximate blackbody cavity bounded by the surrounding walls or apparatus, which are approximately at the air temperature. However, when a radiation shield is used to fend off extraneous radiation which does not correspond to the dry-element temperature, the shield should be polished on the outside, blackened on the inside, and itself be ventilated by the airflow so that it acquires approximately the air temperature. The wet element is then in a blackbody cavity bounded mainly by the blackened surface of the shield.

In accordance with these considerations, the radiation condition chosen for the reference psychrometer is that the wet element is immersed in blackbody radiation corresponding to the dry-element temperature.

4.2 The Form and Orientation of the Wet Element

It will be obvious in retrospect that we have chosen the best geometrical system for the reference psychrometer if we make the choice from only four possibilities. These are the sphere, the symmetrically ventilated wedge-like flat-plate simulator used in the recent studies, the transversely ventilated cylinder, and the axially ventilated cylinder with rounded nose. In considering them, we will bear in mind the four criteria given in Section 3.1.

The sphere is not an easy shape to achieve in practice, and requires a wet-covered supporting stem. This must play a role in determining its temperature. Therefore its radius is not the only length
parameter which influences the properties of the practical system. The sphere is difficult to provide with a smooth, close-fitting wet covering, and is not very amenable to the use of accurate types of thermometers, which almost always have cylindrical sensors. Further, it is not amenable to simple tests to determine its practical equivalence to the ideal.

The flat-plate simulator is not particularly difficult to realize in practice, or to provide with a close-fitting covering. However, it has the same problem with its support as the sphere. Also it has two free edges parallel to the airstream. (Clearly, it is impracticable to make the element, in effect, infinite in the direction of its leading edge.) As well as the airspeed, which must be specified for any system, it requires the specification of an angle, a length, a width, and whatever parameters are needed to define the leading and trailing edges. Except at low Reynolds numbers, the heat-transfer coefficient of the practical element is affected by local turbulence which is influenced by details of the shape. It is not particularly amenable to the accommodation of a cylindrical temperature sensor. The simulator could be used successfully in the recent studies only because special measures were taken to deal with these problems. This was worthwhile because it then provided an absolute standard.

With either transverse or axial ventilation, a cylindrical element is easy to achieve in practice, and, except for the nose in the axial case, is easy to provide with a wet covering. It can easily and effectively accommodate a cylindrical temperature sensor. Further, it lends itself to a procedure which tests for errors due to the conduction of heat along the cylinder from its support. This procedure is to take temperature readings with the temperature sensor in different positions along the length of the element, or, in the axial case, with the wet covering extending to different positions along the length of the element.

From these considerations the choice can obviously be narrowed to a cylindrical type. A point-by-point comparison of the transversely and axially ventilated cylindrical elements is made in Appendix A. The conclusion clearly emerges from that comparison that the transversely ventilated cylinder is superior, and, as already foreshadowed above, it has been adopted for the reference psychrometer.
CHAPTER 5

THE BASIC SPECIFICATION

The basic specification defines the ideal to which the practical reference psychrometer is to approximate. None of its requirements can be achieved exactly in practice.

The specification is such that the dry element acquires the temperature of the airstream, and the wet element conforms to the following requirements:

(i) Has an uncontaminated water surface in the form of an endless cylinder 4.5 mm in diameter.

(ii) Is immersed in blackbody radiation corresponding to the temperature of the airstream.

(iii) Incorporates a temperature sensor in such a manner that the temperature measured is the circumferential-average surface temperature of the element, notwithstanding that the temperature is almost uniform.

(iv) Has incident upon it an infinitely-wide uniform laminar airstream which is at right angles to the axis of the element and has an airspeed which is either

(a) 4.5 m/s regardless of the pressure, temperature and humidity, or

(b) such that, regardless of the pressure, temperature and humidity, it gives a pitot-static pressure difference of 12 Pa (0.12 hPa).

In requirement (iv), (a) and (b) are different alternatives with different practical implications. If (b) is adopted, the airspeed varies somewhat from one set of conditions of pressure, temperature and humidity to another. Within the range of conditions provided for (Chapter 1), the range of airspeed is approximately from 3.7 to 5.3 m/s. To achieve (b) in practice, all that is required is a pitot-static tube and a manometer. The value of atmospheric pressure at the time of the measurements is not required to be known until the measurements (of the wet- and dry-element temperature) are to be reduced to values of humidity. If, on the other hand, (a) is adopted, the airspeed must always be adjusted at the time of measurement to 4.5 m/s. Then, if a pitot-static tube is used to measure the airspeed as is required by the practical specification below, the prevailing atmospheric pressure must be known approximately at the time of the measurements.

The psychrometer coefficient \( A \) of the practical psychrometer differs from that of the ideal psychrometer for broadly two reasons. Firstly, small departures occur through the assignment of tolerances on the wet-element diameter and the airspeed. Secondly, there is an unavoidable compromise in practice in achieving some of the conditions. For example, the practical wet element is of finite length, and so a small amount of heat is conducted into its measuring section from its supports. Also, the airstream incident on the element is confined within a duct, which slightly affects the way in which the air flows over the element. Another deliberate difference, which produces a small but significant change in \( A \), is the use of a wet cotton-sleeve covering to simulate the cylindrical water surface. It is known from experiments carried out in the recent studies that this difference increases \( A \) by a constant 0.4%. The value of \( A \) for the reference psychrometer is given for various pressures, temperatures and relative humidities in tables contained in Chapter 9, below.

The value of \( A \) for the practical psychrometer not only differs slightly from that of the ideal psychrometer, but obviously differs slightly from one practical instrument to another. However, even the value for the ideal psychrometer is known only with a degree of uncertainty. The absolute uncertainty in the value of \( A \) for the practical psychrometer is considered in Chapter 10.
The overall uncertainty in the humidity given by the reference psychrometer arises only partly from that in $A$. It contains also contributions from the uncertainties in the thermometry and, in the field, from the effects of the extraneous radiation which falls on the wet and dry elements. These aspects, too, are considered below.
CHAPTER 6

THE PRACTICAL SPECIFICATION

6.1 Principal Features of the Practical Psychrometer

The principal features of the ducting and the radiation shields associated with the wet and dry elements are shown in Figures 1 to 3. The figures do not show some details specified in the practical specification. Further, in the figures, the diameter of the dry element is shown as being the same as the overall diameter of the wet element (4.5 mm), whereas it will be less by twice the thickness of the wet covering of the wet element.

Air is drawn into the psychrometer through a flared entrance, and then passes in succession through a psychrometer section, an extension section and a reduction section, as labelled in Figure 1. In the psychrometer section, part of the flow enters an inner shield, the passage within which is at first divided by a septum into two similar, parallel parts. These accommodate the wet and dry elements, which are located as shown in the figures. The remainder of the flow passes between the inner and outer shields. The inner shield extends through the psychrometer and extension sections, but the parts of it in these sections are separated by a thermally insulating joint. The outer shield extends continuously through the three sections, and may form the main part of the body of the psychrometer.

Figure 3 shows, cross-hatched and approximately to scale, the boundary layers of the flow for an effective airspeed of 4.5 m/s at standard atmospheric pressure. The corresponding Reynolds number, based on the 4.5 mm overall diameter of the wet element, is approximately 1400. As well as the momentum boundary layers shown, a thermal boundary layer and a vapour boundary layer surround the wet element. The ratio of the thickness of the thermal boundary layer to that of the momentum boundary layer is approximately \( Pr^{-1/3} \), where \( Pr \) is the Prandtl number. For the vapour boundary layer, the corresponding ratio is approximately \( Sc^{-1/3} \), where \( Sc \) is the Schmidt number. As the values of \( Pr \) and \( Sc \) in the present context are not very different from unity, being approximately 0.72 and 0.61 respectively, the momentum boundary layer shown in Figure 3 roughly represents also the thermal and vapour boundary layers. On the leeward side of each element, boundary-layer separation occurs.

The reduction section of the ducting serves to reduce the cross-section of the flow to that of a flexible tube which connects to a fan downstream. It also increases the airspeed, so that pitot and static tubes permanently mounted in the duct near the outlet of the reduction section provide a sufficient pressure difference to allow the use of a simple U-tube manometer.

Among the parts not shown in the figures are the flexible tube leading from the outlet, the temperature sensors which are essentially cylindrical and are a close fit within the stainless-steel tubes of the elements, the water reservoir from which water is fed continuously by capillarity to the wet-element covering, and the pitot and static tubes which, in conjunction with a U-tube manometer, are calibrated in terms of the airspeed of the flow incident on the elements.

6.2 The Ducting, the Shielding and the Positioning of the Wet and Dry Elements (Clauses 1 to 9)

1. The ducting, the principal radiation shields, and the positioning of the thin-walled stainless-steel tubes of the wet and dry elements, shall be as in Figures 1 to 3.

2. The outer shield (duct), inner shield and septum shall be of sheet 18/8 stainless steel 0.50 ± 0.10 mm thick.

3. Although narrow, the leading edges of the outer and inner shields and the septum shall be rounded.
4. Subject to the preferred option expressed at the conclusion of this clause, in the psychrometer section and the extension section both the outer shield and the inner shield shall have clean specularly reflecting stainless-steel outside surfaces and matt black inside surfaces, while both surfaces of the septum shall be matt black. In the reduction section both surfaces of the outer shield shall be bare stainless steel. It is a preferred option that the outer surfaces of the outer and inner shields shall, instead, be so coated as to present clean specularly reflecting aluminium surfaces.

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**Fig. 1.** Plan view (upper diagram) and sectional elevation (lower diagram) of the specified ducting, shielding and wet and dry elements. Dimensions in millimetres.
Fig. 2. Front elevation of the specified ducting, shielding and wet and dry elements.

Fig. 3. Detailed sectional elevation of the specified ducting, shielding and wet and dry elements, showing the boundary layers of the flow approximately to scale (cross-hatched). Dimensions in millimetres.
That part of the inner shield which is in the psychrometer section shall be separated from and thermally isolated from that part which is in the extension section by a thin strip of polyvinylchloride, or material of similar thermal conductivity (about 0.15 W.m\(^{-1}.K^{-1}\)). The size and form of the strip shall be such that its thermal conductance does not exceed that of a strip 2 mm long in the direction of heat flow (parallel to the duct axis) and 3 mm thick perpendicular to the shield. On the outside of the shield, the width of the strip shall not exceed 6 mm, and both outside and inside the shield the strip shall be so shaped as to interfere with the airflow as little as possible.

6. In the fabrication of the assembly comprising the shields and septum, any brackets, fittings, rivets or screws, and any overlaps of sheet metal shall be such that they do not provide appreciable thermal bridges between the different shields (including the septum) and do not add substantially to the thermal capacity of the shields or to the thermal conductance parallel to the axis, and such that there is no appreciable interference with the airflow.

7. Subject to the preferred option expressed in the following sentence, any components or parts of components whose function contributes to the measurement of the temperature of the wet or dry element, or to the supply of water to the wet covering, or to the clamping of the tube of the wet or dry element to the outer shield, shall be shielded from direct sunlight by clean specularly reflecting stainless-steel surfaces. It is a preferred option that the surfaces shall, instead, be clean specularly reflecting aluminium surfaces.

8. It shall be easy for the operator to remove the wet element, complete with wet covering, from the psychrometer and replace it.

9. The construction shall be such that it is possible without undue difficulty to clean all surfaces which, in accordance with Clause 4, are required to be either reflecting or blackened.

6.3 The Wet and Dry Elements (Clauses 10 to 19)

10. The permanent part of each element shall consist of a tube of 18/8 stainless steel of wall thickness 0.10 - 0.016 mm. The length of each tube shall be such that when one end is located midway between the outer and inner shields, the other protrudes outside the opposing wall of the outer shield (Figures 1 and 2), the maximum extent of the protrusion being 3 mm when mercury-in-glass thermometers are used and 10 mm when electrical thermometers are used.

11. The tubes of the wet and dry elements shall be made from the same stock, and so be of the same diameter. (The diameter is not specified directly, but is such that, when the wet covering is fitted to the tube, the overall diameter is in accordance with Clause 16).

12. If there is any possibility that electrical thermometers will be used in the instrument, those ends of the tubes of the wet and dry elements which lie between the outer and inner shields (Clauses 10 and 17) shall be hermetically sealed. The seals shall be such that they are unimpaired by prolonged exposure to water.

13. Each wet- or dry-element tube shall be clamped relative to the outer shield by a device which engages that part of the tube which protrudes outside the outer shield. The device shall locate the tube rigidly as regards longitudinal movement, but itself allow the tube to be tilted, about the clamp as centre, through an angle of not less than 1° in any direction from its central position.

14. The outer surface of the tube of the dry element shall be polished and then coated with aluminium by vacuum deposition.

15. The wet-element covering shall be of seamless cotton sleeving of linear density from 1.5 to 2.5 g/m. The covering shall be free of dressing or size. It shall fit the tube of the element closely
but not tightly.

16. The overall diameter of the wet element, with covering fitted and wet, shall be 4.5 ± 0.5 mm.

17. The wet covering shall extend continuously from a point on the wet element midway between the outer and inner shields at the end through which the temperature sensor is inserted, along the tube to its extremity, and beyond that extremity to the water reservoir.

18. If electrical thermometers are used, then where the wet and dry elements pass through the inner shield (each at two points) they shall be isolated from the shield by bushes or grommets made from PTFE or other chemically inert and hydrophobic thermally insulating material. The bushes or grommets shall fit the wet element (with wet covering) neatly but not tightly. The bushes or grommets provided for the dry element shall be of the same size as those provided for the wet element. If mercury-in-glass thermometers are used, the four grommets shall be omitted, and the holes in the inner shield shall be of such a diameter as to allow a liberal clearance to the wet covering when either thermometer bulb is fitted with such a covering.

19. Any holes made in the outer shield shall be filled or covered to prevent an inflow of air. In particular, the wick shall fill the bush or grommet through which it passes (Clause 21).

6.4 The Water Feed (Clauses 20 to 26)

20. During normal operation of the psychrometer, water shall be supplied continuously to the wet-element covering from a reservoir, along a wick, by capillarity. The wick shall be an extension of the wet-element covering, as implied in Clause 17.

21. A bush or grommet of PTFE or other chemically inert and hydrophobic material shall be provided where the wick passes through the outer shield.

22. The length of the wick from its point of departure from the end of the wet element to the point where it enters the water surface in the reservoir shall not exceed 50 mm.

23. The water surface in the reservoir shall be at a level of from 5 to 20 mm lower than the axis of the wet element.

24. Before the wet element, complete with covering and wick, is inserted in the psychrometer, all parts of the psychrometer which will become wet or will come into contact with wet surfaces, including the water reservoir, the uncovered element, the covering, the wick, and any bushes or grommets in the inner shield which help support the wet element, shall have been cleaned in such a manner that they will not be sources of organic contaminants which will form monomolecular films on water.

25. The insertion of the wet element, complete with covering and wick, shall be effected without contact with the bare hands or other surfaces which can form organic monomolecular films on water.

26. The water added to the water reservoir shall have been prepared by distillation or another purification procedure which results in its surface being free of organic monomolecular films.

6.5 The Airflow and its Measurement (Clauses 27 to 30)

27. Small pitot and static tubes shall be installed permanently within the psychrometer at approximately the outlet of the reduction section. The pitot tube shall be on the axis, and both tubes shall be mounted rigidly.
28. The pitot and static tubes shall be connected to a small U-tube manometer which shall be permanently associated with the psychrometer. The manometer shall contain a liquid which wets glass and is of low toxicity.

29. The psychrometer shall incorporate a means, located downstream of the outlet of the reduction section, whereby the operator can conveniently adjust the airflow to any value from at least 20 per cent less than to at least 20 per cent greater than any operating value which may be required.

30. For normal operation of the psychrometer, and regardless of the pressure, temperature and humidity, the airflow shall be adjusted so that either

(a) The airspeed of incidence of the flow on the wet and dry elements (see Section 8.1) is 3.5 m/s ± 10% or

(b) The manometer reading is such that a pitot-static tube inserted in the airstream incident on the wet or dry element (see Section 8.5) would give a pressure difference of 7.0 Pa ± 20%.

(The reason for the difference between the values of airspeed and pressure difference in this clause and those in the basic specifications of Chapter 5 is given in Section 7.5 and explained in detail in Section 8.3.)

6.6 The Use of Mercury-In-Glass Thermometers (Clauses 31 to 36)

31. Mercury-in-glass thermometers may be used. When such thermometers are used, they shall be specially made, with bulbs of precise outside cylindrical form and diameter, and with the stem adjacent to the bulb formed to a precise cylindrical form of the same diameter as, and concentric with, the bulb.

32. The length of the bulb shall not exceed 35 mm.

33. The bulb, and the adjacent part of the stem for a distance of not less than 65 mm and not more than 70 mm from the centre of the bulb, shall fit the bore of the stainless-steel tube of each element with a diametral clearance of 0.10 ± 0.05 mm. A neck not more than 2 mm wide may exist between the bulb and the adjacent part of the stem.

34. The thermometers shall have a range of 0 to 50°C and, after calibration and allowance for errors of observation in their use, be capable of giving temperatures correct to ± 0.03°C or better. Their scales shall be divided to 0.05°C and shall be not less in length than 350 mm or greater than 500 mm.

35. During normal operation of the psychrometer, the centre of each thermometer bulb shall be located from 3 to 7 mm beyond the centre of that part of the associated stainless-steel tube which lies between the walls of the inner shield.

36. When the psychrometer is operated at nominally a pressure of 1000 hPa, an air temperature of 20°C and a relative humidity of 50%, and with the appropriate airflow (Clause 30), the change in the reading of the wet-element temperature which occurs when the wet-element thermometer is withdrawn from its usual position to a position such that the centre of its bulb is 10 mm outside the range specified in Clause 35 shall not exceed 0.02°C. For purposes of testing the psychrometer for conformity to this requirement, any pressure from 900 to 1100 hPa, any air temperature from 15 to 25°C, and any relative humidity from 40 to 60% may be regarded as representing the nominal.
6.7 The Use of Electrical Thermometers (Clauses 37 to 41)

37. Electrical thermometers of the wire-wound electrical-resistance type or thermocouple type may be used.

38. Each resistance thermometer element or thermocouple junction shall be fitted permanently into and be in close thermal coupling with a cylindrical brass slug the length of which is not less than 15 mm nor greater than 25 mm, and the outside diameter of which is such that its diametral clearance within the stainless-steel tube in which it is inserted is $0.05 \pm 0.03$ mm.

39. During normal operation of the psychrometer, the centre of each brass slug shall be located from 3 to 7 mm beyond the centre of that part of the associated stainless-steel tube which lies between the walls of the inner shield.

40. The resistance-thermometer or thermocouple system shall be capable of giving the individual temperatures of the brass slugs in the wet and dry elements with an uncertainty not exceeding $\pm 0.03^\circ$C.

41. When the psychrometer is operated under the conditions defined and interpreted in Clause 36, the change in the reading of the wet-element temperature which occurs when the brass slug in the wet element is withdrawn from its usual position to a position such that its centre is 10 mm outside the range specified in Clause 39 shall not exceed $0.02^\circ$C.
CHAPTER 7

COMMENTS ON THE PRACTICAL SPECIFICATION

7.1 General Comment

When any fully detailed design for the reference psychrometer is being produced, questions will inevitably arise as to whether some of the clauses of the practical specification need be observed literally. It is not claimed that the features specified are all essential, but rather that they are sufficient. The purposes of some of the clauses can undoubtedly be achieved in alternative ways. However, departures from the specification should be made only when it has been clearly established that they cannot affect the performance or prejudice the ease of management of the psychrometer.

7.2 The Ducting, the Shielding, and the Positioning of the Wet and Dry Elements (Comments on Clauses 1 to 9)

Clause 1 The flared entrance to the duct formed by the outer shield is provided to prevent the airflow separating from the wall on entry, i.e. to prevent a *vena contracta* effect. Its radius (10 mm) has been chosen in the light of the criterion of Hamilton (1929) for flared circular ducts, that the flare radius should be at least 0.14 times the duct diameter, and in the light of the criterion of Harris (1928), also for circular ducts, that an entrance flange should be wider than 0.05 times that diameter. Direct measurements of the uniformity of the airspeed over the cross-section, made with flares which were narrower and of smaller radius than now specified, are reported below. They show that the flares specified must be entirely adequate.

Clause 2 The shields are of such a thickness that they are sufficiently rigid and yet respond at an appropriate rate to temperature changes. The time-constant with which the inner shield and the septum follow changes in the air temperature, which can be estimated after calculating the thermal capacity of the shields and their surface heat-transfer coefficients, is about the same as that for the dry element when mercury-in-glass thermometers are used. For standard atmospheric pressure and an airspeed of 3.5 m/s in the psychrometer section, the value is about 20 seconds. Although the wet element has a greater thermal capacity because of its wet covering, it also has a greater effective heat-transfer coefficient because of the evaporation process, and both for temperature and humidity changes, its time-constant for the pressure and airspeed referred to and for common atmospheric conditions is about 15 seconds. However, in this case the value is rather dependent on the temperature and humidity. The corresponding time-constant for the outer shield (duct wall) in the psychrometer section is about 40 seconds.

Clause 3 The rounding of the edges of the shields is to avoid turbulence and an undue widening of the boundary layers.

Clause 4 The blackening of the inner surfaces of the inner shield and both surfaces of the septum ensures that the elements are largely surrounded by black surfaces at the air temperature. Most of the extraneous radiation which comes through the entrance of the psychrometer and strikes these surfaces is absorbed. The extraneous radiation which enters between the outer and inner shields is largely absorbed on the blackened inside surface of the outer shield, either directly or after a single reflection at the outside surface of the inner shield.

Matt-black enamelled surfaces can absorb 98% of terrestrially emitted thermal radiation or scattered solar radiation. Aluminized, polished stainless-steel surfaces can reflect 97% of terrestrially emitted thermal radiation and 86% of scattered solar radiation.
Aluminium surfaces on stainless-steel shields may be achieved by attaching aluminized thin polymer film (eg polyester film) with a suitable adhesive. If the aluminium coating is sufficiently thick, its durability can be considerably improved without serious loss of reflectance if it is anodized before the film is attached to the surface, to form an anodic coating about 2 μm thick. The aluminium should not be so thick that it contributes significantly to the thermal conductance of the shields, i.e., should not be more than about 10 μm thick.

The blackening on the shield surfaces, and any attached sheet material or associated adhesive, should be resistant to alcohol as well as water.

**Clause 5**  The convective heat-transfer coefficient at the surface of each shield and the septum, diminishes in the downstream direction. Thus the inner shield in the psychrometer section is more effective than that in the extension section, from which it is thermally isolated to preserve its greater efficacy and shorter time-constant.

**Clauses 6 to 9**  Require no comment.

### 7.3 The Wet and Dry Elements (Comments on Clauses 10 to 19)

**Clause 10**  Use of the stainless-steel tubes for the wet and dry elements allows the thermometers (of whatever type) to be removed and replaced very easily. It also allows the temperature sensors to be moved to different positions along the length of the tubes to confirm that infinite cylinder conditions have been achieved (Section 8.2). The similarity of the wet- and dry-element tubes allows the dry element to be converted temporarily to a matching wet element for testing purposes.

**Clause 11**  The closely equal sizes of the wet- and dry-element tubes means that similar thermometer bulbs or brass slugs will fit them properly. (Clauses 33 and 38).

**Clause 12**  Requires no comment.

**Clause 13**  The provision for tilting ensures that when mercury-in-glass thermometers are fitted they can be located without over-constraint and possible breakage.

**Clause 14**  The aluminized surface of the dry element increases the reflectance for extraneous radiation.

**Clause 15**  Requires no comment.

**Clause 16**  The diameter of the stainless-steel tubes of the wet and dry elements should be such that this specification of the overall diameter of the wet element is met with the particular cotton sleeving used. If the sleeving is too thick, the tube diameter will be inconveniently small.

**Clause 17**  The extension of the wet-element covering to the water reservoir constitutes the wick.

**Clause 18**  The bushes or grommets should not constrict the flow of water along the covering. The use of bushes or grommets of the same size for both elements preserves the possibility of converting the dry element to a wet element for testing purposes. The dry element is consequently less accurately located, but this is not very important.

**Clause 19**  Requires no comment.

### 7.4 The Water Feed (Comments on Clauses 20 to 26)

**Clauses 20 and 21**  Require no comment.
Clauses 22 and 23  An excessive length of wick or difference in level of the water in the reservoir and the axis of the wet element would unnecessarily impede the flow of water to the wet covering. Under dry, hot conditions, considerable demands are made on the water feed. If any part of the wet covering is at a lower level than the water surface in the reservoir, siphoning and consequent dripping are likely to occur.

Because of the requirement of Clause 23, it is likely to be more convenient if the wet element is in the upper position.

Clauses 24 to 26  The importance of avoiding organic contaminants which can form monomolecular films on a water surface, and especially the natural grease of the hands, has been shown in the recent studies. However, a very effective simple procedure for removing monolayers from the wet-element surface has been demonstrated in those studies, and its use in the present context is called for below (Section 11.2).

7.5  The Airflow and its Measurement (Comments on Clauses 27 to 30)

Clause 27  It is much easier to use separate pitot and static tubes, than the concentric combination commonly encountered. As the relationship between the pressure difference and the airspeed of the flow incident on the wet and dry elements is to be determined experimentally for each detailed design of the reference psychrometer, the wall pressure may be adopted for the static pressure, and a small metal tube perforating the duct wall following the end of the reduction section and finishing flush with the inside surface may be used.

Clause 28  Alcohol, perhaps with a small amount of a dye added, is a suitable liquid for the manometer. Its density may be taken to be 0.790 kg/L.

Clause 29  Requires no comment.

Clause 30  The values of airspeed and pitot-static pressure difference in Clause 30 differ from those in the basic specification (Chapter 5) because in the practical psychrometer the airflow is confined in a duct. This aspect is considered in detail below (Section 8.3).

The pitot-static pressure difference referred to is equal to the reduction which occurs in the static pressure of the air as it moves from the surrounding atmosphere into the entrance part of the psychrometer section. Therefore, it can be measured as the difference in pressure between a static tube in that part of the psychrometer section and the ambient atmosphere.

Between the psychrometer section and the outlet of the reduction section, the airspeed increases by a factor of about 5.5. For a pitot-static pressure difference of 7.0 Pa in the psychrometer section, the pressure difference of the pitot and static tubes installed near the outlet of the reduction section is about 21 mm head of water, but is to be found by calibration (Section 8.5).

7.6  The Use of Mercury-in-Glass Thermometers (Comments on Clauses 31 to 36)

Clauses 31 to 34  Sample thermometers of the type specified have been made by Karl Schneider und Sohn, of Wertheim, Germany, and the Yoshino Instrument Company, Toshima-ku, Tokyo, Japan.

When the psychrometer is operated in a practically stationary atmosphere, and the observer cannot approach closely without affecting the observations, an optical aid in the form of a simple telemicroscope might be desirable to read the thermometers.

Clause 35  Because of the conduction of heat in the thermometer stem, the centre of the range of position of the thermometer bulb which gives a negligible immersion error is beyond the centre of that part of the associated stainless-steel tube which lies between the walls of the inner shield.
Clause 36  The test procedure implied by this clause, which should be carried out in the laboratory, is exemplified below, where some results obtained with sample thermometers are given. The results were obtained with a couple of drops of water added within each stainless-steel tube, to fill the clearance space between the thermometer bulb and the inside surface of the tube. With mercury-in-glass thermometers, but not with electrical thermometers, this device may be employed whenever it is desired to improve the effective immersion, or even routinely.

7.7  The Use of Electrical Thermometers (Comments on Clauses 37 to 41)

Clause 37  Not only electrical resistance thermometers of the wire-wound type, but also thermocouples, for example of copper and constantan, are easily capable, when properly calibrated, of meeting the required accuracy, which is given in Clause 40. The electrical insulation must be adequate.

Clause 38  The use of a brass slug greatly facilitates the attainment of good thermal contact with the inside surface of the tube. It is easy to ensure that the diameter of the slug is such that the required diametral clearance is obtained.

Clause 39  Experimental results given below show that, as is to be expected, the centre of the range of position of a slug which gives a negligible immersion error is beyond the centre of that part of the associated stainless-steel tube which lies between the walls of the inner shield.

Clause 40  With electrical thermometers, and especially thermocouples, provision can often be made for the direct measurement of the temperature difference. It is then possible for the uncertainty in the temperature depression to be considerably less than the value of 0.042°C which corresponds to the wet- and dry-element temperatures being measured independently with an uncertainty of 0.03°C. This results in a still higher overall accuracy of the reference psychrometer, especially for laboratory applications.

Clause 41  Again, the test should be carried out in the laboratory. In the particular example for which experimental results are given in Section 8.2, the requirement of this clause is met.
CHAPTER 8

TESTS AND ANCILLARY CALIBRATIONS

8.1 Measurement of the Distribution of the Airflow

Provided the requirements of Section 6.2 and those of Clauses 19 and 30 are met, the distribution of the airflow in the psychrometer section of the instrument is determined by the design given in Figures 1 to 3. Therefore, once it has been shown that this design gives a satisfactory distribution, neither the maker nor the user of the psychrometer need concern himself further with this aspect.

Experiments have been carried out to determine the distribution in an instrument constructed by CSIRO. As the measurements were made at a relatively early stage, they relate to entrance-flare radii of 5 mm, rather than 10 mm. However, as the smaller radius is the less conducive to a uniform flow, the measurements are conservative in this respect. Further, the measurements were made at an airspeed about 40% higher than the specified value. As the higher airspeed is less conducive to uniformity, the measurements are conservative in this respect also.

The wet and dry elements were removed from the psychrometer and the holes left in the shields covered with adhesive tape. To restore the flow resistance to approximately its original value, cylinders representing the wet and dry elements were wedged between the walls of the inner passages downstream in the plane of the trailing edge of the septum. The airspeed distribution was explored with a static tube of 1 mm outside diameter with four holes of 0.33 mm diameter drilled around the circumference at a distance of 8 mm from an approximately ellipsoidal nose. The reference pressure was that of the surrounding atmosphere, which equals the total head of the flow. The results for cross-sections 6, 13 and 20 mm from the leading edge of the inner shield are given in Figures 4 and 5.

The distributions for the channels normally occupied by the wet and dry elements are naturally very similar. At the 13 mm cross-section, close to the plane normally occupied by the elements, and in the lateral region within which the elements are free of significant immersion errors, the airspeed is uniform within a few percent. This degree of uniformity is entirely adequate.

The precise meaning of the expression *airspeed of incidence* used below is the airspeed on the axis, 13 mm downstream from the leading edge of the inner shield, with the elements substituted by dummy elements downstream as described in this section.

8.2 Test for Infinite Cylinder Conditions

If it is found that a central length of the wet element exists within which the temperature sensor can be moved without a significant change in the observed temperature, then it can be concluded, for that length, that infinite cylinder conditions have been adequately approximated and the effect of heat conducted along the wet-element tube and along the wet-element thermometer stem or leads is negligible.

Using an instrument constructed by CSIRO, temperature explorations have been made by moving the wet-element temperature sensor within its tube, both for electrical and mercury-in-glass thermometers. The dry element was converted to a wet element by the addition of a second wet covering, making the instrument symmetrical as regards the two elements. Then, by observing the difference in the temperatures of the two sensors, the effect of changing the position of either one could be determined without problems due to small changes in the temperature and humidity of the atmosphere.
Fig. 4. The observed airspeed distribution along the major axes of the cross-sections of the inner channels at distances of 6, 13 and 20 mm from the leading edge of the inner shield (Fig. 1).
Fig. 5. The observed airspeed distribution along the minor axes of the cross-sections of the inner channels at distances of 6, 13 and 20 mm from the leading edge of the inner shield (Fig. 1).
For the electrical sensors, a differential thermocouple of 0.15 mm copper and 0.23 mm constantan, with its junctions soldered into brass slugs 13 mm long, was used. The brass slugs do not accurately model those specified in Clause 38 for the normal operation of the psychrometer, which are required to be 15 to 25 mm long, but were made shorter so that a better indication of the true temperature distribution would be obtained. The stainless-steel tubes of the elements were of 4.0 mm outside diameter and 0.11 mm wall thickness, and the diametral clearance between the slugs and the inside surfaces of the tubes was 0.04 mm. No attempt was made to keep the thermocouple leads against the inside surfaces. With an airspeed of incidence of approximately 5.0 m/s, an air temperature of approximately 20°C and a wet-element temperature depression of 7.1°C, the results plotted in Figure 6 were obtained by moving each slug in turn.

In Figure 6, the displacement scale indicates the position of the centre of the slug relative to the centre of that part of the tube which lies between the walls of the inner shield. The results for the two elements are closely similar. The variation in the observed temperature is less than 0.01°C for a range of position of more than 30 mm. Because of the conduction of heat in the thermocouple leads (especially the copper lead, for the thermal conductivity of copper is about seventeen times greater than that of constantan), the centre of that range is displaced to a position about 5 mm beyond the centre of the tube.

The test shows that the error in the temperature of the 13 mm slug is negligible as long as the slug is wholly contained within a range of length of approximately 45 mm. A slug 25 mm long, but of the same diameter as the 13 mm slugs and attached to similar thermocouple leads, could be displaced by more than 10 mm from a central position within this range for a temperature error of 0.02°C (Clause 41).

**Fig. 6.** The indicated wet-element temperature for different positions of the temperature sensor along the wet-element tube. With both elements operating as wet elements, a result is obtained for each. For sensors comprising thermojunctions fixed in brass slugs, as described in Section 8.2, and the conditions described in that section.
Corresponding tests have been carried out with mercury-in-glass thermometers. However, because of an early change in the design, the sample thermometers available did not have a sufficient length of stem reduced to the bulb diameter to allow the thermometers to be inserted far enough for the centres of their bulbs to reach the centres of the tubes. The results given in Figure 7, which were obtained under approximately the same conditions as those for the electrical sensors, show that the attainable immersion was nevertheless adequate. Filling the clearance space between the thermometer bulb and the inside surface of each tube with water, by adding a couple of drops within the tube, only slightly changed the range of position for a constant temperature reading, but improved the reproducibility outside that range. The results given were obtained with the water present.

Fig. 7. The indicated wet-element temperature for different positions of the bulb of a mercury-in-glass thermometer along the wet-element tube. With both elements operating as wet elements, a result is obtained for each. These results were obtained with mercury-in-glass thermometers the features and manner of use of which are described in Section 8.2, and for the conditions described in that section.

8.3 Airflow Regime and its Effect on the Psychrometer Coefficient $A$

As compared with the flow around the wet element in the infinitely wide airstream of the basic specification (Chapter 5), the flow around the element in the instrument is modified by its confinement within the inner shield. For a given uniform airspeed upstream of the element, the presence of the shield increases the airspeed in the neighbourhood of the element. The airspeed affects the value of $A$ practically only through the radiation and $a$ factors (Section 2.2). Therefore, the effective airspeed must be defined as the airspeed with which an infinitely wide (unconfined) airstream would have to be incident on the element to give the same value of the convective heat-transfer coefficient $h_c$, and hence same value of the convective mass-transfer coefficient $k_c$, as occurs in the instrument. It is the effective airspeed, denoted in this report by $v_e$, which must, nominally, have the value 4.5 m/s which occurs in the basic specification (Chapter 5). However, the observed airspeed is the airspeed of incidence, a precise definition of which has been given in Section 8.1.

In the original report on the WMO Reference Psychrometer (Wylie and Lalas, 1981a) the small difference between $v$ and the airspeed of incidence was considered so uncertain that, instead of an allowance being made for it, it was simply represented by an additional uncertainty of 0.4% in $A$. This corresponds to an average additional uncertainty of about 17% in $v$. In the present publication we make an allowance for the difference, and incorporate the associated uncertainty in $v$.

Various workers have studied the relationship between $v$ and the airspeed of incidence for flows confined in small wind tunnels, and their results have been reviewed by Morgan (1975).
Following Morgan, we adopt the formula of Vincenti and Graham. When this is applied to the present instrument with approximate allowances for the thicknesses of the boundary layers of the flow, it gives the result that \( v \) exceeds the airspeed of incidence by 29%. However, the uncertainty in this amount is estimated to be about half. Thus, with the airspeed of incidence set to 3.5 m/s ± 10% (Section 6.5, Clause 30), the value of \( v \) is 4.5 m/s ± 15%.

By comparing a reference psychrometer with free-standing transversely ventilated wet and dry elements in a wind tunnel, the present authors attempted to measure the effect of the above airspeed increase on the value of the psychrometer coefficient \( A \). The airspeed of incidence was equalized with the airspeed in the wind tunnel. The difference in \( A \) is then expected to be approximately 0.5%. However, the overall accuracy of such a comparison proved to be insufficient to allow a significant difference to be detected. Again, the results of the accurate direct comparison of a WMO Reference Psychrometer with a standard gravimetric hygrometer carried out by Fan (1987) do not imply a significant difference (see Section 9.1).

### 8.4 Thermometer Calibrations and Related Matters

The practical specification leaves it to the maker or user of the psychrometer to ensure that, when the psychrometer is used, the true temperature of the bulb or brass slug of each thermometer, within the limits of error specified by Clause 34 or Clause 40, is obtained from the thermometer readings. The thermometers should have been properly calibrated. Also, in the case of mercury-in-glass thermometers, which are generally calibrated in an erect position, a correction to the reading of each thermometer is likely to be necessary for the fact that, in the instrument, the thermometers are used in a horizontal position, and an emergent-stem correction must also be applied to the reading of the wet-element thermometer.

Mercury-in-glass thermometers should be calibrated under conditions of total immersion with sufficient accuracy to ensure that the requirements of Clause 34 can be met. To determine the correction necessary when using them horizontally, the change in reading when they are inverted in the calibration bath may be observed and divided by two. Provided the 0°C graduation mark on the wet-element thermometer is not far from the outer shield when the thermometer is in the psychrometer, the emergent-stem correction will be given with sufficient accuracy by

\[
\text{correction in } ^\circ\text{C} = - 0.00016 \left( T - T_w \right),
\]

where \( T_w \) and \( T \) are respectively the wet- and dry-element temperatures in Celsius. This correction has its greatest value of −0.10°C when \( T = 50°C \) and \( T_w = 25°C \).

Experience in the recent studies shows that when a group of copper-constantan thermocouples is calibrated at 13 points from 0 to 60°C, and the results are fitted by a cubic polynomial, the standard deviation of the fit can be 0.004°C. Digital microvoltmeters are available commercially which will display the emf directly with adequate accuracy.

Platinum resistance thermometer elements suitable for the psychrometer are available commercially. They should be fitted to their brass slugs before calibration, in case a small strain effect occurs with change of temperature. Four leads should extend from within the tube of each element to the resistance-measuring instrument. Bridges are available commercially which can measure the resistance with adequate accuracy.

It may be noted that, to obtain the true temperature of the ambient atmosphere, corrections should in principle be applied to the observed dry-element temperature to allow for the cooling due to the adiabatic expansion of the air as it accelerates into the psychrometer, and for the adiabatic-wall heating which occurs at the element. For an effective airspeed of 4.5 m/s, the former amounts to approximately −0.010°C, while the latter, which has been found in the recent studies to be practically the same for the transversely ventilated cylinder as for the classical flat-plate system (Schlichting, 1968), amounts to approximately +0.008°C. However, the net effect is entirely negligible.
8.5 Calibration of the Airspeed-Measurement System

The system comprising the pitot and static tubes installed in the psychrometer and the associated manometer must be calibrated in terms of the airspeed of the stream incident on the wet element. This calibration need be carried out only once for any particular detailed design of the reference psychrometer. It should, therefore, be performed by the maker, but the user may wish to verify it.

The wet element should be removed from the instrument, and the holes left in the shields covered with adhesive tape. As in the experiments described in Section 8.1, to restore the flow resistance to approximately its original value, a cylinder representing the wet element should be wedged between the walls of the wet-element passage downstream. A small static tube, the pressure given by which is referenced on atmospheric pressure, may then be used to measure the airspeed on the axis of the wet-element passage at the position normally occupied by the element, while simultaneous observations are made of the manometer reading. The static tube described in Section 8.1 is suitable. Instruments are available commercially which can directly indicate the very small pressure difference which the tube gives. It is desirable to determine the ratio of that pressure difference to the pressure difference indicated by the manometer for airspeeds of incidence from about 2.5 to 4.5 m/s. It should vary so little that it can be approximated to a constant value.

If the type of liquid used in the manometer is ever changed, then, of course, account must be taken of any difference in the liquid density.
CHAPTER 9

DATA AND FORMULAE FOR THE PSYCHROMETER COEFFICIENT \( \lambda \)

9.1 Bases of the Given Data and Formulae

As seen in Section 2.1, the humidity either in the form of the vapour mole fraction or the relative humidity can be derived from \( T, T_w \) and \( p \) by means of equations (1) and (2) and the definition of the relative humidity when the appropriate value of \( \lambda \) is known. Although, as already noted, \( \lambda \) is only slightly dependent on \( T, T_w, p \) and the airspeed, the dependence is significant in the present context. Tables of \( \lambda \) for appropriate ranges of conditions, and formulae from which \( \lambda \) can be calculated, are therefore given.

The data and formulae for \( \lambda \) are based on

(a) A procedure in which the value of \( \lambda \) for transversely ventilated cylindrical wet elements has been linked with that for simulators of the classical flat-plate system by direct experimental comparisons (Wylie, 1979), and the latter has been obtained by a priori calculation using the complete theory (Wylie, 1985). With the calculation of the radiation and \( k \) factors (Section 2.2), the experiments have shown that the value of \( \lambda_e \) for the transversely ventilated cylinder exceeds that for the flat-plate system by a constant 0.7% over a wide range of Reynolds numbers. The procedure gives \( \lambda \) for a wide range of conditions with an uncertainty of about 1% which arises largely from that in the literature data for the diffusivity of water vapour in air.

(b) Extensive direct measurements of \( \lambda \) for transversely ventilated cylinders, carried out by Wylie and Lalas (1981a; 1985). The work involved wide ranges of temperature and airspeed, but a single nominal diameter of 1.75 mm and an airstream of zero water content, the only value which could be established with sufficient accuracy. The uncertainty in the results exceeds 0.3% only for the highest wet-element temperatures.

(c) A direct experimental determination of \( \lambda \) for a WMO Reference Psychrometer, carried out in Beijing (Fan, 1987). A reference psychrometer constructed by the Academy of Meteorological Science (of China) was compared with a standard gravimetric hygrometer developed by the National Institute of Metrology. The results give the \( \lambda \) of the reference psychrometer for temperatures approximating 23°C and relative humidities of 40 to 50%. The uncertainty is 0.8%.

To compare, collate or use the results of (a), (b) and (c), account must be taken of the small differences of \( \lambda \) for wet-element coverings of woven cotton sleeveing as used in the reference psychrometer, eg in (c), wound cotton yarn as used in the experiments of (b), and a smooth water surface as assumed in (a). These differences are obtainable from further results of the direct experimental comparisons of wet elements (Wylie, 1979) which show that, for a wide range of the Reynolds number, the value of \( \lambda_e \) with the sleeveing is greater by a constant amount of 0.4%, and with the cotton yarn greater by a constant amount of 0.2%, than with a smooth water surface.

In the experiments of (b), the wet element was confined in a rectangular duct in an arrangement analogous to that in the reference psychrometer. Although some allowance was made in the original analysis for the consequent difference between the effective airspeed and that observed, it has since been recognized as being too small. The results have therefore recently been completely reanalysed with the allowance for the confinement of the flow estimated on the same basis as now adopted for the reference psychrometer (Section 8.3). The effect has been that the values of \( \lambda \) given by Wylie and Lalas (1981a; 1981b; 1985) have been revised upwards by 0.3 to 0.4%.
Even before this revision was made, the results of (a) and (b) agreed over the range of (b) well within the statistical aggregate of the uncertainties involved. With the revision the agreement is even closer. When, further, the literature-based value originally used for the diffusivity of water vapour in air is adjusted by an appropriate small amount, well within its uncertainty, the differences between the individual results of (b) and corresponding results of (a) become purely random, and the rms difference for the three different wet elements and eighty-one different sets of conditions (of temperature from 11° to 58°C, and airspeed from 0.5 to 5 m/s) is approximately 0.3%. With the adjusted diffusivity, (a) may therefore be used to calculate \( A \) for wide ranges of the parameters. Calculated in this way for the reference psychrometer, the value of \( A \) for the conditions of (c) is \( 6.23 \times 10^{-4} \) \( \text{K}^{-1} \), while the value given by Fan’s painstaking measurements, after an upwards adjustment of approximately 0.5% for his use of the originally specified airspeed of incidence of 4.5 m/s rather than the 3.5 m/s now specified (Section 8.3), is \( 6.26 \times 10^{-4} \) \( \text{K}^{-1} \). The difference is well within the statistical aggregate of the uncertainties.

It is clear from these considerations that to obtain \( A \) accurately for the reference psychrometer we may use procedure (a) with the slightly adjusted value of the diffusivity of water vapour in air and, of course, the due small allowance for the wet-element covering being of woven cotton sleeveing.

9.2 Tables of \( A \)

Values of \( A \) for the WMO Reference Psychrometer constructed and operated as specified in this publication are given in Tables 2 to 5 for various pressures, air temperatures and relative humidities. They have been obtained in the way described at the conclusion of Section 9.1, and their accuracy is considered in Section 10.2.

Values of \( A \) for pressures corresponding to altitudes near sea level are given in Tables 2 and 3, which are respectively for a constant effective airspeed of 4.5 m/s and the airspeed of incidence which corresponds to a constant pilot-static pressure difference of 7.0 Pa. Values for pressures corresponding to high altitudes are similarly given in Tables 4 and 5.

9.3 Formulae for \( A \)

Formulae from which values of \( A \) of adequate accuracy can be calculated are given both because they can conveniently be incorporated in computer programs and because they allow \( A \) to be calculated for values of the wet-element overall diameter which depart from the nominal value specified in Clause 16 and for values of the airspeed which depart from the nominal value specified or implied by Clause 30. The wet-element overall diameter is required by Clause 16 to be \( 4.5 \pm 0.5 \) mm, but the diameter may be measured more accurately than required. If, for example, the diameter is known to be \( 4.7 \pm 0.2 \) mm, the value of 4.7 might be used in the calculation of \( A \). Similarly, the airspeed or static-pressure drop may be known more accurately than is required by Clause 30.

To avoid a formulation of undue complexity, separate formulae are given for the three component factors of \( A \), namely \( A_v \), the radiation factor and the \( \alpha \) factor (Section 2.2), while for \( A_\alpha \), the formula which Wylie and Lallas (1981b; 1985) obtained for zero humidity is used as an approximation. Small differences which exist between values of \( A \) given by the formulation and those given in the tables arise largely from the approximation. Should it be desired to apply corrections for these, reference may be made to a tabulation (or alternatively a formula) given by Wylie and Lallas (1981b; 1985). However, although, within the present range of conditions, values of \( A \) given by the formulation can differ from those given by the tables by as much as \(-1\%\), the corresponding difference in the relative humidities deduced from given values of \( T, T_w \) and \( p \) does not exceed 0.1% relative humidity. This is because the difference in \( A \) is greatest for conditions for which the derived humidity is relatively insensitive to \( A \).

With the wet-element overall diameter in mm, the effective airspeed \( v \) in m/s (see Section 8.3), the atmospheric pressure \( p \) in hPa and the temperatures in kelvins, and putting \( T_m \) for \( 0.5(T + T_w) \) and denoting \( 1 - x_w \), the radiation factor and the \( \alpha \) factor respectively by \( F_x \), \( F_r \) and \( F_\alpha \), the required
formulae may be written
\[ A_c = F_x [5.897 \times 10^{-4} + 4.97 \times 10^{-7} (T_w - 273.15)] \] \hspace{1cm} (6)

\[ F_x = 1 + [4.77 \times 10^{-3} T_w^{-3} d^{0.539} (pv)^{-0.462}] \] \hspace{1cm} (7)

\[ F_s = 1 + [0.0131 T_w^{0.9} v^{0.461} (pd)^{-0.539} F_x^{-1}] \] \hspace{1cm} (8)

and equation (3) becomes
\[ A = A_c F_x F_s \] \hspace{1cm} (9)

For the present range of conditions, a constant value of \( f_w \) of 1.004 may be used in conjunction with this formulation (cf Table 1).

A segment of FORTRAN which uses these equations to derive the vapour mole fraction \( x \), the vapour partial pressure \( e \) and the relative humidity \( U \) for given values of \( T \), \( T_w \) and \( p \) is given in Appendix B. Included also in that appendix is a segment which calculates the wet-element temperature \( T_w \) for given values of \( T, p \) and \( U \), and another which gives the saturation vapour pressure of pure water and its temperature dependence, both as a function of temperature. A skeletal table of test values is given for each segment.
Table 2. Values of the Psychrometer Coefficient $A$ for Sea-Level Pressures, a Wet-Element Overall Diameter of 4.5 mm, and an Effective Airspeed of 4.5 m/s

$A \times 10^4 (K^{-1})$

<table>
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<th>30</th>
<th>40</th>
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Table 3. Values of the Psychrometer Coefficient $A$ for Sea-Level Pressures, a Wet-Element Overall Diameter of 4.5 mm, and the Airspeed of Incidence which Corresponds to a Pitot-Static Pressure Difference of 7.0 Pa

$A \times 10^4 \ (K^{-1})$

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Table 4. Values of the Psychrometer Coefficient $A$ for Low Pressures, a Wet Element Overall Diameter of 4.5 mm, and an Effective Airspeed of 4.5 m/s.

$A \times 10^4$ (K^(-1))
Table 5. Values of the Psychrometer Coefficient $A$ for Low Pressures, a Wet-Element Overall Diameter of 4.5 mm, and the Airspeed of Incidence which Corresponds to a Pitot-Static Pressure Difference of 7.0 Pa

$A \times 10^4 \text{ (K}^{-1}\text{)}$

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CHAPTER 10

UNCERTAINTY IN THE DERIVED HUMIDITY

10.1 Effect of the Uncertainty in the Atmospheric Pressure

Consider firstly the dependence of the derived relative humidity $U$, vapour mole fraction $x$ and vapour partial pressure $e$ on the pressure $p$. From equations (1) and (2) it is found that, for any conditions, an error of 1% in $p$ and an error of 1% in $A$ result in approximately equal errors in $U$. Thus, if $p$ is known to the nearest hectopascal it to ±0.5 hPa or 1 in 2000 for $p = 1000$ hPa so that the uncertainty in $p$ is less than one tenth of that in $A$ (0.8%), the effect of the uncertainty in $p$ on the derived relative humidity may be neglected.

Also, it is found that, as the humidity approaches zero, an error of 1% in $p$ and an error of 1% in $A$ result in approximately equal errors in $x$, and that, as the relative humidity approaches 100%, an error of 1% in $p$ results in approximately a −1% error in $x$. Clearly, with $p$ known to the nearest hectopascal the effect of the uncertainty in $p$ on the derived vapour mole fraction may also be neglected.

It is further found that an error in $p$ produces a fractional error in the vapour partial pressure $e$ which is always either less than or equal to the fractional error which it produces in the vapour mole fraction. Therefore, the same uncertainty again in the pressure does not contribute significantly to the uncertainty in the derived vapour partial pressure, either.

It may be concluded that, when the value used for $p$ is correct to the nearest hectopascal, the uncertainties in the derived values of $U$ and $x$ may be considered to arise only from those in $A$, $T$ and $T_w$, and that the uncertainty in $e$ is practically the same as in $x$.

10.2 The Uncertainty in the Psychrometer Coefficient $A$

The uncertainty in $A$ is the same whether the psychrometer is used in the laboratory or in the field. It includes the uncertainty in our knowledge of the $A$ of the psychrometer of the basic specification (Chapter 5), a small uncertainty arising from an adjustment for the type of wet-element covering, and uncertainties arising from those in the diameter and the effective airspeed. Although $A$ depends to some extent on the atmospheric conditions, the uncertainty in $A$ contributed by the uncertainties in those conditions is entirely negligible.

Our best data for $A$ (Chapter 9) relate to the system of the basic specification, but with a wet-element covering of wet cotton yarn rather than a smooth water surface. Their uncertainty exceeds 0.3% only for the highest wet-element temperatures. When these data have been increased by 0.2% to allow for the covering in the practical psychrometer being of wet cotton sleeveing, their uncertainty may conservatively be regarded as increased to 0.4%.

For present purposes the uncertainty in the wet-element overall diameter is regarded as equal to the tolerance of 0.5 mm in 4.5 mm (11%), assigned in Clause 16. That in the effective airspeed is regarded as 15% (see Section 8.3). This means that it is assumed that all that is known about the diameter and the airspeed of incidence is that they conform to the assigned tolerances. The uncertainty in $A$ arising from that in the diameter, calculated for the worst case, namely the lowest pressure (650 hPa), the highest temperature (50°C) and the highest wet-element temperature (35°C), is then found to be 0.4%. The uncertainty arising from that in the effective airspeed has its greatest value, namely 0.5%, for those same conditions. The overall uncertainty in $A$ is the statistical sum of the components, which rounds upwards to 0.8%. The tables of $A$ given in Section 9.2 (Tables 2 to 5)
CHAPTER 10

apply to the reference psychrometer, as specified, with this uncertainty.

10.3 The Uncertainties in the Wet- and Dry-Element Temperatures

For laboratory applications of the reference psychrometer, the uncertainties in $T$ and $T_w$ are simply those contributed by the thermometry, which for present purposes are regarded as having the maximum allowed value of 0.03°C (Clauses 34 and 40). The uncertainties in $T$ and $T_w$ may or may not be correlated. If they are uncorrelated, as when mercury-in-glass thermometers are used, the maximum uncertainty in $T - T_w$ is 0.042°C. However, if they are positively correlated, as occurs with some systems of electrical thermometry the maximum uncertainty in $T - T_w$ is less than this value. As the derived humidity is considerably more sensitive to $T - T_w$ than to $T$, the correlation increases the accuracy of the psychrometer. The overall uncertainties tabulated for laboratory application of the psychrometer in Section 10.4 have been calculated on the basis that the uncertainties in $T$ and $T_w$ are uncorrelated.

For field applications of the reference psychrometer, errors in $T$ and $T_w$ due to the effects of extraneous radiation must also be considered. In a field investigation carried out in Sydney, the effects of the scattered solar radiation and terrestrially emitted thermal radiation which reach the wet and dry elements of the psychrometer have been determined for representative sky conditions both in summer and in winter. An account of the investigation is given in Appendix C. It shows, among other things, that a horizontal orientation of the reference psychrometer generally limits the radiation error in the derived humidity to smaller values than an orientation in which the wet and dry elements see only the sky or the ground. The horizontal orientation has consequently been adopted, and only the results for that orientation are used here.

In Appendix C, the results of the field investigation have been used to calculate the average radiation errors and the associated uncertainties which would occur in the relative humidity for an air temperature of 20°C and relative humidities of 20, 50 and 80%. Some conservative but approximate general inferences are then made in that appendix solely on the basis of those calculations. However, in the following the results have been used to calculate the average radiation errors and the associated uncertainties for practically the whole range of conditions allowed.

Twenty-seven field experiments were carried out with the instrument horizontal, but here (unlike in Appendix C) we will discard the results of one of the experiments which are particularly divergent. From the results of each of the remaining twenty-six experiments we can deduce, for the conditions of the experiment, the radiation error $\Delta T$ which would occur in the temperature of the dry element, and the radiation error $\Delta T_w'$ which would occur in the temperature of the wet element if (hypothetically) evaporation from that element did not occur. In these forms, the errors depend on the particular radiation conditions, but have practically no direct dependence on the temperature and humidity. Also, as it is the difference in temperature between terrestrial sources and the air that is the main factor determining the effect of the terrestrial component of the extraneous radiation, the errors have no obvious indirect dependence on the temperature or humidity. In fact, the sets of values of $\Delta T$ and $\Delta T_w'$ are very similar for summer and winter. Therefore, although the radiation conditions are, no doubt, correlated to some degree with the air conditions, it is reasonable for present purposes to regard the results of the field experiments in the form of $\Delta T$ and $\Delta T_w'$, as applicable for any temperature and humidity.

Those results may be summarized by stating that the twenty-six values of $\Delta T$ have an average of 24 mK and a standard deviation of 9 mK, that those of $\Delta T_w'$ have an average of 104 mK and a standard deviation of 51 mK, and that the variation in $\Delta T$ and that in $\Delta T_w'$ are positively correlated, with a correlation coefficient of 0.62. The correlation is important, as it significantly reduces the uncertainty which the extraneous radiation contributes to the derived humidity.

Now, the radiation error $\Delta T_w'$ in the temperature of the actual wet element is less than $\Delta T_w'$ because it is limited not only by an increase in the direct transfer of heat from the element but also by an increase in the rate of evaporation from the element. Specifically, $\Delta T_w'$ is obtained from $\Delta T_w'$ by
dividing by the factor $j$ (of the order of 3) given by

$$j = 1 + \frac{f_{\beta}}{\Delta p}$$

(10)

where $\beta$ is the rate of change of the saturation vapour pressure of pure water with temperature at the temperature of the wet element. For present purposes, the factor $f_{\beta}$ in this equation may be approximated to unity. It should be clearly understood that $j$ and hence $\Delta T_w$, unlike $T_w$, depend on the wet-element temperature and so on the conditions of the air.

Therefore, noting that the correlation coefficient for $\Delta T$ and $\Delta T_w$ is the same as for $\Delta T$ and $\Delta T_w$, we may summarize the effect of the extraneous radiation by stating that

(i) The radiation error in $T$ is $+24$ mK with an uncertainty of $18$ mK (twice the standard deviation).

(ii) The radiation error in $T_w$ is $+(104/j)$ mK with an uncertainty of $(102/j)$ mK.

(iii) The uncertainties given in (i) and (ii) are positively correlated with correlation coefficient 0.62.

Strictly, for field work, corrections of $-24$ mK and $-(104/j)$ mK should be applied to the measured values of $T$ and $T_w$ respectively. The uncertainties of $18$ mK and $(102/j)$ mK are uncertainties in $T$ and $T_w$ respectively, and, together with the correlation between them, they affect the uncertainty in the derived humidity. The uncertainties of $0.03^\circ$C which are contributed to $T$ and $T_w$ by the thermometry, and which we will assume are uncorrelated, also affect the uncertainty in the derived humidity.

10.4 The Overall Uncertainty for Laboratory Applications

For laboratory applications of the reference psychrometer, the component uncertainties in the relative humidity, which arise from the uncertainty of 0.8% in $A$ and the uncertainties of $0.03^\circ$C in $T$ and $T_w$, combine statistically to give the overall uncertainties seen in Table 6. The table includes values for a pressure of 1000 hPa representing sea level, and for a pressure of 700 hPa representing high altitudes. They have been calculated for a constant effective airspeed of 4.5 m/s, but the values for a constant pitot-static pressure difference of 7.0 Pa are practically the same.

<table>
<thead>
<tr>
<th>Temperature ($^\circ$C)</th>
<th>Pressure (hPa)</th>
<th>Relative Humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>10</td>
<td>1000</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>0.41</td>
</tr>
<tr>
<td>20</td>
<td>1000</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>0.29</td>
</tr>
<tr>
<td>30</td>
<td>1000</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>0.21</td>
</tr>
<tr>
<td>40</td>
<td>1000</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>0.15</td>
</tr>
<tr>
<td>50</td>
<td>1000</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>0.11</td>
</tr>
</tbody>
</table>

For sea level, and nominally $20^\circ$C and 50% relative humidity, the overall uncertainty is 0.30% relative.
humidity. The uncertainty diminishes rapidly with increasing temperature, but is not very dependent on the relative humidity. It is slightly smaller at high altitudes. In general, it is attributable mainly to the uncertainties in $T$ and $T_w$, but, more specifically, mainly to that in $T - T_w$, to the effect of which the uncertainty in $T$ adds little. The overall uncertainty can be reduced to a significant but, except at high relative humidities, not large extent by measuring $T$ and $T_w$, and particularly $T - T_w$, more accurately than required or implied by the specification.

    Corresponding values of the overall uncertainty in the derived vapour mole fraction $x$ are given in Table 7. The comments made concerning the values in Table 6 apply also to those in Table 7, except that, being expressed as a percentage, the uncertainty in $x$ is markedly dependent on the relative humidity, tending to infinity as the humidity approaches zero.

    The uncertainties given in Tables 6 and 7 apply when the uncertainties in the diameter, the airspeed and the wet- and dry-element temperatures all have the maximum values allowed. The actual uncertainties in these quantities could, however, be smaller than those values.

### Table 7. Uncertainty in the Derived Vapour Mole Fraction $x$ for Laboratory Applications of the Reference Psychrometer

<table>
<thead>
<tr>
<th>Temperature ($^\circ$C)</th>
<th>Pressure (hPa)</th>
<th>Relative Humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>10</td>
<td>1000</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>1.8</td>
</tr>
<tr>
<td>20</td>
<td>1000</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>1.2</td>
</tr>
<tr>
<td>30</td>
<td>1000</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>0.86</td>
</tr>
<tr>
<td>40</td>
<td>1000</td>
<td>0.77</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>0.61</td>
</tr>
<tr>
<td>50</td>
<td>1000</td>
<td>0.56</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>0.45</td>
</tr>
</tbody>
</table>

#### 10.5 The Overall Uncertainty for Field Applications

As seen in Section 10.3, values are available for the radiation errors in $T$ and $T_w$, averaged over various radiation conditions. As it is not intended that in using the psychrometer the operator should distinguish between the radiation conditions on different occasions, these averages are in the nature of known constant errors, for which corrections could be applied. As seen in Section 10.3, the variations in the actual radiation errors from one occasion to another are taken into account by associated uncertainties.

Here we tabulate the net effect of those average errors on the derived humidity, and the overall uncertainty which would exist in the derived humidity if a correction were applied for that net effect. The former quantity has two components, which arise respectively from the error of $+24$ mK in $T$ and the error of $+(104/j)$ mK in $T_w$. These components must be added algebraically. The latter quantity, the overall uncertainty, has components which arise from the uncertainty of $0.8\%$ in $A$, the thermometric uncertainties of $0.03^\circ$C in $T$ and $T_w$, and the radiation uncertainties of $18$ mK in $T$ and $(102/j)$ mK in $T_w$. The last two of these components are negatively correlated, with correlation coefficient $-0.62$. The five components are aggregated by summing their squares and subtracting the
correlation term $2 \times 0.62 \times 18 \times (102/j)$ from the sum.

The resulting net errors and overall uncertainties in the relative humidity are given for pressures of 1000 and 700 hPa in Table 8. The error changes from a positive to a negative value with increasing temperature. Its generally surprisingly small value is attributable to a partial cancellation of the components associated with $T$ and $T_w$. At the lower temperatures the latter, and at the higher temperatures the former, component predominates. The overall uncertainty is, of course, somewhat larger than, but has generally the same trend as, that in Table 6.

Table 8. Radiation Errors and Overall Uncertainties in the Derived Relative Humidity $U$ for Field Applications of the Reference Psychrometer

<table>
<thead>
<tr>
<th>Temperature ($^\circ$C)</th>
<th>Pressure (hPa)</th>
<th>Relative Humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>10</td>
<td>1000</td>
<td>+0.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.68</td>
</tr>
<tr>
<td>700</td>
<td>+0.28</td>
<td>+0.25</td>
</tr>
<tr>
<td></td>
<td>0.52</td>
<td>0.49</td>
</tr>
<tr>
<td>20</td>
<td>1000</td>
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</tr>
<tr>
<td></td>
<td>0.43</td>
<td>0.39</td>
</tr>
<tr>
<td>700</td>
<td>+0.15</td>
<td>+0.12</td>
</tr>
<tr>
<td></td>
<td>0.34</td>
<td>0.30</td>
</tr>
<tr>
<td>30</td>
<td>1000</td>
<td>+0.12</td>
</tr>
<tr>
<td></td>
<td>0.29</td>
<td>0.26</td>
</tr>
<tr>
<td>700</td>
<td>+0.08</td>
<td>+0.05</td>
</tr>
<tr>
<td></td>
<td>0.23</td>
<td>0.20</td>
</tr>
<tr>
<td>40</td>
<td>1000</td>
<td>+0.07</td>
</tr>
<tr>
<td></td>
<td>0.20</td>
<td>0.18</td>
</tr>
<tr>
<td>700</td>
<td>+0.05</td>
<td>+0.02</td>
</tr>
<tr>
<td></td>
<td>0.16</td>
<td>0.14</td>
</tr>
<tr>
<td>50</td>
<td>1000</td>
<td>+0.04</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
<td>0.13</td>
</tr>
<tr>
<td>700</td>
<td>+0.03</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>0.11</td>
<td>0.10</td>
</tr>
</tbody>
</table>

The corresponding errors and uncertainties in $x$ are given in Table 9. In this case, although the two components of the error are of opposite sign, they do not become equal in magnitude within the range of the table, the net error remaining positive and decreasing with increasing temperature throughout.

Instead of a correction being applied for the radiation error, the value adopted for the overall uncertainty may be increased. The absolute value of the radiation error may be added directly to the overall uncertainty at the 95% confidence level. For example, for $p=1000$ hPa, $T=20^\circ$C and $U=50\%$ relative humidity, the radiation error of $+0.14\%$ relative humidity (Table 8) may be combined with the uncertainty of $0.38\%$ relative humidity to give a comprehensive uncertainty of $0.52\%$ relative humidity. An analogous course may be followed for the vapour mole fraction and the vapour partial pressure. For meteorological applications, this essentially conservative course is recommended.
CHAPTER 10

Like the uncertainties given in Tables 6 and 7, those given in Tables 8 and 9 apply when the uncertainties in the diameter and the airspeed, and those contributed by the thermometry to the wet- and dry-element temperatures, all have the maximum values allowed.

Table 9. Radiation Errors and Overall Uncertainties in the Derived Vapour Mole Fraction $x$
for Field Applications of the Reference Psychrometer

<table>
<thead>
<tr>
<th>Temperature ($^\circ$C)</th>
<th>Pressure (hPa)</th>
<th>0</th>
<th>20</th>
<th>40</th>
<th>60</th>
<th>80</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1000</td>
<td>$\approx$</td>
<td>+2.0</td>
<td>+1.0</td>
<td>+0.67</td>
<td>+0.50</td>
<td>+0.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\approx$</td>
<td>3.2</td>
<td>1.5</td>
<td>1.0</td>
<td>0.74</td>
<td>0.60</td>
</tr>
<tr>
<td>700</td>
<td></td>
<td>$\approx$</td>
<td>+1.4</td>
<td>+0.71</td>
<td>+0.47</td>
<td>+0.35</td>
<td>+0.28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\approx$</td>
<td>2.4</td>
<td>1.2</td>
<td>0.75</td>
<td>0.56</td>
<td>0.46</td>
</tr>
<tr>
<td>20</td>
<td>1000</td>
<td>$\approx$</td>
<td>+1.1</td>
<td>+0.53</td>
<td>+0.35</td>
<td>+0.27</td>
<td>+0.21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\approx$</td>
<td>2.0</td>
<td>0.91</td>
<td>0.59</td>
<td>0.45</td>
<td>0.37</td>
</tr>
<tr>
<td>700</td>
<td></td>
<td>$\approx$</td>
<td>+0.74</td>
<td>+0.37</td>
<td>+0.25</td>
<td>+0.19</td>
<td>+0.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\approx$</td>
<td>1.5</td>
<td>0.70</td>
<td>0.46</td>
<td>0.36</td>
<td>0.30</td>
</tr>
<tr>
<td>30</td>
<td>1000</td>
<td>$\approx$</td>
<td>+0.58</td>
<td>+0.29</td>
<td>+0.19</td>
<td>+0.15</td>
<td>+0.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\approx$</td>
<td>1.3</td>
<td>0.59</td>
<td>0.39</td>
<td>0.30</td>
<td>0.26</td>
</tr>
<tr>
<td>700</td>
<td></td>
<td>$\approx$</td>
<td>+0.41</td>
<td>+0.20</td>
<td>+0.14</td>
<td>+0.10</td>
<td>+0.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\approx$</td>
<td>0.98</td>
<td>0.46</td>
<td>0.32</td>
<td>0.26</td>
<td>0.23</td>
</tr>
<tr>
<td>40</td>
<td>1000</td>
<td>$\approx$</td>
<td>+0.34</td>
<td>+0.17</td>
<td>+0.11</td>
<td>+0.08</td>
<td>+0.07</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\approx$</td>
<td>0.86</td>
<td>0.41</td>
<td>0.28</td>
<td>0.23</td>
<td>0.20</td>
</tr>
<tr>
<td>700</td>
<td></td>
<td>$\approx$</td>
<td>+0.24</td>
<td>+0.12</td>
<td>+0.08</td>
<td>+0.06</td>
<td>+0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\approx$</td>
<td>0.67</td>
<td>0.33</td>
<td>0.24</td>
<td>0.20</td>
<td>0.19</td>
</tr>
<tr>
<td>50</td>
<td>1000</td>
<td>$\approx$</td>
<td>+0.20</td>
<td>+0.10</td>
<td>+0.07</td>
<td>+0.05</td>
<td>+0.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\approx$</td>
<td>0.61</td>
<td>0.30</td>
<td>0.22</td>
<td>0.19</td>
<td>0.17</td>
</tr>
<tr>
<td>700</td>
<td></td>
<td>$\approx$</td>
<td>+0.14</td>
<td>+0.07</td>
<td>+0.05</td>
<td>+0.04</td>
<td>+0.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\approx$</td>
<td>0.48</td>
<td>0.25</td>
<td>0.20</td>
<td>0.17</td>
<td>0.16</td>
</tr>
</tbody>
</table>
CHAPTER 11

OPERATION OF THE REFERENCE PSYCHROMETER

11.1 Initial Preparation

Before the psychrometer is first used for humidity measurement, calibration results for the thermometers (Section 8.4) and the airspeed-measurement system (Section 8.5) should be available, and the test in clause 36 or 41 should have been carried out with satisfactory results. Care should have been taken that mercury-in-glass thermometers are not mechanically overconstrained, resulting in pressure on the bulbs. This can affect the readings. Indeed, it has been observed that the readings of one pair of thermometers made for the reference psychrometer were increased by 0.06°C just through the change in hydrostatic pressure in the bulbs which resulted from turning them from a vertical to a horizontal position.

Care should also have been taken that the thermometer bulbs in the case of mercury-in-glass thermometers, or brass slugs in the case of electrical thermometers, have not been displaced from their correct positions within the stainless-steel tubes. Further, with electrical thermometers, it should have been confirmed that the electrical insulation is adequate.

These and other preparations and precautions are of obvious importance, but what is more necessary under the present general heading is to consider the steps which should be taken, both in the initial preparation of the psychrometer and during its use, to ensure that the wet-element surface is free from significant organic monolayer (or multilayer) films when observations are made.

11.2 Achievement and Preservation of a Clean Wet-Element Surface

It is necessary to consider the initial cleaning of the wet-element covering and wick, the cleaning of surfaces which will or might come into contact with the covering or with the feed water, and the handling of the covering when it is being fitted to the wet-element stainless-steel tube or when the covered element is being fitted to the psychrometer. It is necessary also to describe a simple flooding procedure which has been found to remove residual organic films very effectively. Further, it must be explained how it can be known that no significant films remain on the surface.

While an attempt must be made to achieve a wet-element surface which is already sufficiently clean on fitting the wet element, it has been found that the probability of significant organic contamination remaining on the surface at that stage is not negligible. The flooding procedure is, therefore, an essential routine. However, it is also essential that, on fitting the wet element to the instrument, there should be no more than a trace of organic contamination on the surface. This can then be removed rapidly, but the flooding might have to be repeated many times to remove the contamination that would result, for example, from holding the wet element between the bare fingers.

The cotton sleeving to be used for the covering and wick should be cut to length and, together with any length of cotton thread which may be required to secure the covering when fitted, should be degreased, first with a distilled organic solvent and then by boiling in a 5% aqueous solution of caustic soda. It should then be boiled in successive portions of distilled water. For the initial degreasing, distilled alcohol or acetone is suggested.

The vessels used in these operations should be of glass and should be small. Any implements, such as forceps, which may be used, should be of stainless steel, and the vessels and implements should be properly cleaned. The object of cleaning them should be to remove or destroy organic contaminants rather than to remove all traces of water-soluble matter. One way of achieving this is to raise them to a temperature of about 500°C in a suitable oven.
Excess water should be removed from the washed sleeveing with the aid of fresh filter papers, and the sleeveing then allowed to dry between such papers. The sleeveing should be dry when fitted to the wet-element tube and when the wet-element assembly is fitted to the psychrometer.

The water reservoir of the psychrometer, which is best made of glass, and also the stainless-steel tubes of the elements, may be cleaned along with the vessels and implements used in preparing the covering. Any bushes or grommets through which the elements or wick pass may be cleaned with a distilled solvent. The shield surfaces and any other surfaces in the neighbourhood of the elements or wick, and particularly where the bushes or grommets are to be fitted, should, of course, be cleaned in situ. This is best achieved by delivering alcohol to the surfaces from a small wash bottle, similar to that to be used to flood the wet element with water, as described below. (Acetone might attack the matt-black surfaces or other parts of the instrument, and in any case is unduly toxic for use in this manner.)

The manipulations involved in fitting the (dry) cotton sleeve to the wet-element tube, in tying any thread, and in then fitting the assembly to the psychrometer, are difficult to carry out solely with implements such as forceps. However, the hands may be used provided they are covered with thin disposable polyethylene gloves of the type available inexpensively in packs for medical use. Obviously, the gloved hands will not remain clean unless contact with them is confined to clean surfaces.

Once the covered wet element has been fitted to the instrument, clean water may be added to the reservoir, and the water allowed to progress along the cotton sleeve by capillarity. The final stage of cleaning, namely the flooding procedure, is to deliver an excess of clean water directly to the wet-element covering from the reduced tip of a glass tube which is part of a small wash bottle, e.g., squeeze bottle, so that drops of water fall from the covering. The wet element should be kept horizontal, so that the excess water does not bridge across any supporting bushes or grommets. The falling drops may be collected on fresh filter papers inserted against the lower wall of the duct, which is likely to be the septum. In this procedure, residual organic films are removed rapidly on the surfaces of falling drops. The procedure may easily be repeated at any time during normal operation of the psychrometer.

In order to know that the particular procedure followed is adequate, and to know how long the wet-element surface will remain free of significant surface films with continued operation in a particular atmosphere, experience should be gained of operating the psychrometer with both elements fitted with wet coverings. It is not necessary to provide a wick for the covering on what would normally be the dry element.

It is best if the temperature difference between the two wet elements is measured directly, e.g., by a differential thermocouple with its junctions in brass slugs. Working in the laboratory under reasonably uniform and steady conditions, the temperature difference when the two wet surfaces are clean should be no more than a few millikelvins. The effect of a film may be observed if one is formed deliberately on one element, e.g., by adding a few drops of surface-contaminated water with the aid of a glass rod. When the consequent temperature difference has been observed, the flooding procedure may be employed, and the temperature difference, which should then be very small, again observed.

To determine the length of time for which the psychrometer can be operated in any particular atmosphere before an initially clean wet-element surface acquires a significant degree of contamination, use may be made of the following procedure. The instrument may be operated in the particular atmosphere for a period with two wet elements after which it may be removed to the laboratory and one of the wet-element surfaces cleaned by the flooding procedure. The temperature difference observed when the instrument is then operated indicates the effect of the contamination acquired. It is likely to be found that in most atmospheres a significant degree of contamination develops only after a lengthy period of operation.

Once a conservative estimate of the necessary frequency of flooding has been made, the covering may be removed from the normally dry element, and the psychrometer used in the normal way. The flooding procedure, which can be carried out very rapidly, may then be employed whenever
there is the least doubt as to the cleanliness of the wet-element surface.

It is suggested that, when the instrument is not to be used for a period, it should be covered against dust, perhaps with sheet polyethylene in the form of a bag. It is then likely that, on the next occasion on which the instrument is used, the flooding procedure will suffice to give a clean wet-element surface.

11.3 Operation in the Laboratory

It may be noted that to test some types of hygrometers, particularly working psychrometers, it can be sufficient to compare them with the reference psychrometer under just one set of conditions, which may be chosen more or less arbitrarily. Therefore, operation of the reference psychrometer simply in the atmosphere of a room can be valuable, even if the conditions in the room cannot be varied significantly. Such single-point comparisons can yield the value of the psychrometer coefficient $A$ for a working psychrometer or give valuable evidence as to the systematic error in a Deweel-type hygrometer or working dew-point hygrometer.

To make comparisons under different sets of conditions it is easiest if use can be made of different rooms the atmospheres of which are normally controlled to substantially different conditions. Unfortunately, a sufficiently large space which can be set to different conditions, and which gives conditions which are sufficiently uniform and steady, is a rare facility and a costly one to provide. However, rooms which are not temperature or humidity controlled, but are simply isolated, such as large storage areas below ground level, can be just as suitable as controlled rooms, and can often provide conditions which are steadier and more uniform.

A great advantage is gained if the wet- and dry-element temperatures are recorded continuously. This implies the use of electrical thermometers. Particularly if the output of the instrument being tested is also recorded continuously, this allows errors due to drifts and fluctuations in the conditions to be discounted considerably, as the observer can choose to read those sections of the recordings which correspond to the more steady conditions, and can draw average lines through the recorded traces. With digital outputs from the thermometers of the reference psychrometer and the instrument under test, data-processing procedures can be employed which achieve the same advantages with less involvement of the observer.

If an instrument to be checked against the reference psychrometer itself incorporates a thermometer (eg a Deweel-type or dew-point instrument) or thermometers (eg another psychrometer), then that thermometer or those thermometers should be calibrated separately first.

As already said above, the thermometers and the airspeed-measurement system of the reference psychrometer should have been calibrated, and the instrument prepared with due attention to cleanliness, especially as regards organic contaminants (Section 11.2). The instrument should be set up with the axis of its ducts and those of its wet and dry elements approximately horizontal. If there is a perceptible flow of air around the psychrometer, then the inlet should face into the flow. The outlet of the airflow of the psychrometer should be some distance from the inlet, and should be directed towards an air-conditioning or ventilation outlet, if there is one.

The airspeed should be set according to the manometer reading, and the appropriate corrections applied to the thermometer readings. With mercury-in-glass thermometers, these include the correction for the thermometers being in a horizontal position (Section 8.4) and the emergent-stem correction given by equation (5). The flooding procedure described in Section 11.2 should be carried out rather more often than the exploratory work recommended in that section would indicate to be necessary.
CHAPTER 11

11.4 Operation in the Field

Operation in the field is required mainly for the testing of meteorological humidity and temperature instrumentation, as considered in Chapter 1. The World Meteorological Organization (WMO) has considered that it is satisfactory to locate such instrumentation above "a plot of level ground covered with short grass and about 9 m by 6 m in size", provided this is suitably sited (WMO, 1983). The experiments which have been carried out to determine the effects of extraneous radiation on measurements made with the reference psychrometer, and which are reported in Appendix C, were performed over a level area of short grass. In the field, the reference psychrometer should, as far as possible, be positioned above such an area. However, there may be no alternative but to use whatever area has been provided for the instruments which have to be tested.

The reference psychrometer should be supported on a mounting comprising one or more slender polished aluminium struts. A single vertical aluminium tube about 50 mm in diameter is suitable. The instrument should be located at approximately the same height as, and neither directly upwind nor directly downwind of, that to be tested.

We cannot become involved here in the question of what should be meant by the humidity or temperature at a site. This is for the meteorologist to define. However, WMO not only describes the features of a suitable site, but specifies that surface humidity and temperature measurements should be made at a height of 1.25 m to 2 m above ground level (WMO, 1983).

The reference psychrometer should be so positioned that the axis of its ducts and those of its wet and dry elements are approximately horizontal. Also, the direction of the airflow in the instrument should make angles of less than 90° with the azimuth of the sun and with the direction (of flow) of the wind. These requirements cannot be satisfied if the wind and the sun's rays come from the same direction (azimuth). If this condition occurs and the wind is light, the axis of the psychrometer may be set almost perpendicular to the azimuth of the sun, but no direct sunlight must fall on the entrance of the psychrometer. Ideally, the instrument should face into the wind, with the sun's rays coming from some direction well behind the entrance. It should not face the surface of any sunlit structure which occupies more than a small fraction of the external field of view of the wet and dry elements.

Clearly, conditions can be encountered under which the readings of the reference psychrometer, like those of the installed instruments, would not be very meaningful. These include conditions in which rain or snow is being precipitated and conditions in which a strong wind is laden with sea-spray or dust. Such conditions are, however, not more prohibitive for the use of the reference psychrometer than for most other types of hygrometers.

Under very hot, dry conditions, heavy demands are made on the capillary water feed to the wet-element surface. The cotton-sleeve covering may be considered to be sufficiently wet if it glistens when illuminated by a strong beam of light. In the field, a beam of sunlight may be directed onto the covering with the aid of a small mirror held in the hand. If the water is insufficient, the situation can be improved by tilting the psychrometer about its axis, so that the flow is aided by gravity. However, the flow must not be sufficient to cause water drops to form on and fall from the covering.

There would appear to be nothing to be gained by using the reference psychrometer for field comparisons under very variable conditions, such as result from continuous large variations in the intensity of the sun due to clouds, or from gusty strong winds or intermittent showers of rain. All the information required can be obtained if comparisons are confined to reasonably steady conditions, which can include a wide range from full sun to general overcast, strong wind to calm, and high to low humidities. The results are then much more definitive. Further, in regard to the effects of variations, it is obvious that the advantages of continuous recording are still much greater in field work than in laboratory work, and the outputs of both the reference psychrometer and the instruments under test should be recorded simultaneously if possible.

As regards the attention necessary to the reference psychrometer itself, and the need to take
certain precautions and apply appropriate corrections, most of the remarks made in Section 11.3 apply also for operation in the field. However, in field work, the fan which draws air through the psychrometer should be located on or near the ground at a distance of about 2 m downwind of both the reference psychrometer and the instruments under test, and the outflow should be directed with the wind.
ACKNOWLEDGEMENTS

Assistance from Mr P. J. R. Shaw, Mr E. E. Jesson and Ms S. M. Tickner, of the Australian Bureau of Meteorology, in the presentation of the final text is gratefully acknowledged.

REFERENCES

[For an introduction to the literature of psychrometry, see Wylie (1979), Wylie and Lallas (1981b) and Wylie (1985)].


SYMBOLES

(This list does not include the symbols in FORTRAN which are defined in Appendix B, or the special groups of symbols defined in Appendix C.)

A Usual psychrometer coefficient. Equation (1).
A_C Convective psychrometer coefficient. Equation (3).
B_C Basic psychrometer coefficient. Equation (4).
d Wet-element overall diameter. Equations (7) and (8).
e Water vapour partial pressure. Following equation (2).
e_q Saturation vapour pressure of pure water at the temperature T. Appendix B.
e_w Saturation vapour pressure of pure water at the temperature T_w. Equation (2).
F Radiation factor. Equation (7).
F_x Equals 1-x_w. Equation (6).
F_x The factor. Equation (8).
f_w Factor defined by equation (2).
h_c Convective heat-transfer coefficient. Equation (3).
h_r Radiative heat-transfer coefficient. Equation (3).
j Factor defined by equation (10).
k_c Convective vapour-transfer coefficient. Equation (3).
k_a Vapour-transfer coefficient associated with a. Equation (3).
Pr Prandtl number. Section 6.1.
p Atmospheric pressure. Equation (2).
Sc Schmidt number. Section 6.1.
T Dry-element (or air) temperature. Equation (1).
T_m Mean of T and T_w. Equation (7).
T_w Wet-element temperature. Equation (1).
U Relative humidity. Following equation (2).
v Airspeed. Equations (7) and (8).
x Water vapour mole fraction. Equation (1).
x_s Saturation value of x for the temperature T. Following equation (2).
x_w Saturation value of x for the temperature T_w. Equation (1).
α Evaporation (equally condensation) coefficient. Following equation (3).
β Temperature derivative of e_w. Equation (10).
APPENDIX A

A Comparison of the Transversely and Axially Ventilated Cylindrical Psychrometer Systems.

For the purposes of the point-by-point comparison of the transversely and axially ventilated cylindrical wet-element systems which is given in Table A1, we have adopted values of the parameters pertinent to the reference psychrometer. Further, we have assumed standard atmospheric pressure and average temperatures and humidities.

The comparison has required an approximate knowledge of the convective heat-transfer coefficients. For the axial system with a well streamlined nose, which implies a roughly ellipsoidal rather than a hemispherical shape, the convective heat-transfer coefficient is roughly the same as for the classical flat-plate system. That for the transverse system is known accurately (Wylie, 1979).

Of the nine points of comparison in Table A1, the first seven clearly indicate considerable advantages for the transversely ventilated system. Point 8 indicates that it is possible with axial ventilation to achieve a completely laminar boundary layer. Such a boundary layer offers some possibility of an a priori theoretical analysis of the properties of the system. However, it can only be achieved in practice at airspeeds so low that the radiation factor, which is already high (Point 5) becomes unacceptably so, leading to an excessive sensitivity to the longitudinal dimension and the airspeed. The one significant advantage of the axial-flow system is seen in Point 9. However, the significance of a low volume rate of flow depends on the application. It becomes important if the psychrometer is to be used in a confined space, but such an environment is neither necessary nor suitable for a reference psychrometer.

The comparison clearly indicates the superiority of the transversely ventilated system for a reference psychrometer, or, indeed, for any psychrometer intended for precise measurements.
## APPENDIX A

### TABLE A1

A Point-by-Point Comparison of the Transversely and Axially Ventilated Cylindrical Psychrometer Systems

<table>
<thead>
<tr>
<th>Transversely Ventilated</th>
<th>Axially Ventilated</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The shape and size of the wet element are defined by a single length parameter, the diameter.</td>
<td>The shape and size of the wet element are defined by the diameter, a longitudinal dimension (two, if the temperature sensor does not fill the nose), and whatever parameters are needed to define the shape of the nose.</td>
</tr>
<tr>
<td>2. The distance over which the temperature must be averaged by the temperature sensor is of the order of the diameter, say 4.5 mm.</td>
<td>The distance over which the temperature must be averaged by the temperature sensor is of the order of the length, say 30 mm.</td>
</tr>
<tr>
<td>3. A wet covering with a well-defined surface shape and texture is easy to provide.</td>
<td>For the nose of the element, it is difficult to provide a wet covering with a well-defined surface shape and texture.</td>
</tr>
<tr>
<td>4. It is easy to test for infinite-cylinder conditions, including freedom from errors due to longitudinal heat conduction, by moving the temperature sensor along the element.</td>
<td>It is possible to test for errors due to longitudinal heat conduction, by allowing the wet covering to extend to different distances along the element. (Not much can be learned by moving the sensor along the element, because the local temperature always increases slightly with distance from the nose.)</td>
</tr>
<tr>
<td>5. For a diameter of 4.5 mm and an airspeed of 4.5 m/s, the Reynolds number is approximately 1400, and the radiation factor increases $A$ by approximately 5.4%.</td>
<td>For a temperature sensor 30 mm long and an airspeed of 4.5 m/s, the Reynolds number is about 9200, and, for a smooth surface with an ellipsoidal nose, the radiation factor increases $A$ by approximately 11.6%.</td>
</tr>
<tr>
<td>6. In practice, the flow regime corresponding to the conditions in the preceding point prevails for Reynolds numbers from less than 100 to about 2000.</td>
<td>In practice, the flow regime which occurs for the conditions in the preceding point involves boundary-layer turbulence, and is sensitive to the shape of the nose and the Reynolds number.</td>
</tr>
<tr>
<td>7. The flow regime is insensitive to an angle of yaw.</td>
<td>The flow regime is sensitive to an angle of yaw.</td>
</tr>
<tr>
<td>8. Separation of the boundary layer always occurs on the leeward side.</td>
<td>At low Reynolds numbers (in practice, well below 9000 because of the roughness of the wet element covering) the flow over the surface is purely laminar. The radiation factor is then substantially greater.</td>
</tr>
<tr>
<td>9. The system does not have a particularly compact form, and, for the same airspeed, requires a much larger volume rate of flow of air than the axially ventilated system.</td>
<td>The system has a compact form, and, for the same airspeed, requires a much smaller volume rate of flow of air than the transversely ventilated system.</td>
</tr>
</tbody>
</table>
APPENDIX B

Computer Program Segments and Related Test Values

In this appendix, segments of FORTRAN based on the formulation for $A$ in Section 9.3 of the text are given for the derivation of the humidity from observations made with the psychrometer, and for the calculation of the wet-element temperature for given atmospheric conditions. In each case, a table of sample values is given for checking purposes. A subroutine needed for these segments, which gives the saturation vapour pressure of pure water (Wexler, 1976) and its temperature derivative, is included. A table of sample values is given for this also.

The formulation given in Section 9.3 and hence the related program segments and tables of test values given in this appendix, differ slightly from those given in 1977. This is because the formulation given in 1977 could be based only on the work subsequently reported by Wylie (1979), while the present, more accurate formulation is based more on the later direct experimental determination of $A$ reported by Wylie and Lalas (1981).

B1. The following segment gives the vapour mole fraction $X$ (a ratio), the vapour partial pressure $E$ (hPa) and the relative humidity $U$ (percent) for given values of the wet- and dry-element temperatures and of atmospheric pressure.

\[
T = \text{observed dry-element temperature} \quad \text{(in K)}
\]
\[
TW = \text{observed wet-element temperature} \quad \text{(in K)}
\]
\[
P = \text{known atmospheric pressure} \quad \text{(in hPa)}
\]
\[
C
\]
\[
D = \text{wet-element overall diameter} \quad \text{(in mm)}
\]
\[
V = \text{airspeed} \quad \text{(in m/s)}
\]

\[
\begin{align*}
FW &= 1.004 \\
\text{CALL PEBET} (T,ES,BET) \\
XS &= 0.01 \times FW \times ES / P \\
\text{CALL PEBET} (TW,EW,BET) \\
XW &= 0.01 \times FW \times EW / P \\
FX &= 1.0 - XW \\
TM &= 0.5 \times (T + TW) \\
AC &= FX \times (5.897E - 4 + 4.97E - 7 \times (TW - 273.15)) \\
FR &= 1.0 + 4.77E - 8 \times TM \times TM \times TM \times D \times 0.539 / (P \times V) \times 0.461 \\
FA &= 1.0 + 0.0131 \times SQRT(TW) \times V \times 0.461 / (FX \times (P \times D) \times 0.539) \\
A &= AC \times FR \times FA \\
X &= XW - A \times (T - TW) \\
E &= X \times P \\
U &= 100.0 \times X / XS
\end{align*}
\]

Sample values of the relative humidity $U$ (percent) calculated by this segment are given in Table B1. They relate to a wet-element overall diameter of 4.5 mm and an effective airspeed of 4.5 m/s, and are for pressures of 700 and 1000 hPa and various wet- and dry-element temperatures.
### Table B1. Sample Values of the Relative Humidity $U$ (percent) for $d = 4.5$ mm and $v = 4.5$ m/s

<table>
<thead>
<tr>
<th>$T_w$ ($^\circ$C)</th>
<th>$T$ ($^\circ$C)</th>
<th>$p = 700$ hPa</th>
<th>$p = 1000$ hPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>5</td>
<td>53.4</td>
<td>9.4</td>
<td>(values negative)</td>
</tr>
<tr>
<td>10</td>
<td>100.0</td>
<td>33.9</td>
<td>8.4</td>
</tr>
<tr>
<td>15</td>
<td>63.6</td>
<td>24.8</td>
<td>8.3</td>
</tr>
<tr>
<td>20</td>
<td>100.0</td>
<td>44.8</td>
<td>19.9</td>
</tr>
<tr>
<td>25</td>
<td>69.6</td>
<td>34.1</td>
<td>16.9</td>
</tr>
<tr>
<td>30</td>
<td>100.0</td>
<td>51.7</td>
<td>27.4</td>
</tr>
<tr>
<td>35</td>
<td>73.4</td>
<td>40.4</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>(values &gt; 100%)</td>
<td>100.0</td>
<td>56.4</td>
</tr>
<tr>
<td>45</td>
<td>76.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>100.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**B2.** The wet-element temperature $T_w$ (K) may be calculated for a given dry-element temperature, atmospheric pressure, and relative humidity by the following segment, which uses an iteration procedure to refine an initial very rough estimate.

```
T = observed dry-element temperature  (in K)
P = known atmospheric pressure  (in hPa)
U = known relative humidity  (percent)

C
D = wet-element overall diameter  (in mm)
V = airspeed  (in m/s)

C
FW = 1.004
CALL PEBET (T, ES, BET)
XS = 0.01 * FW * ES / P
X = 0.01 * U * XS
W = 100.0 - U
TW = T - (0.02 * W + 3.7E - 4 * W * W) * (1.0 + 0.1 * (T - 273.15))

C
DO 5 L = 1.2
CALL PEBET (TW, EW, BET)
XW = 0.01 * FW * EW / P
FX = 1.0 - XW
TM = 0.5 * (T + TW)
AC = FX * (5.897E - 4 + 4.97E - 7 * (TW - 273.15))
FR = 1.0 + 4.77E - 8 * TM * TM * TM * D * 0.539 / (P * V) * 0.461
FA = 1.0 + 0.0131 * SQRT(TW) * V * 0.461 / (FX * (P * D) * 0.539)
A = AC * FR * FA
G = 1.0 / (1.0 + 0.01 * FW * BET / (A * P))
TW = TW - G * ((XW - X) / A - (T - TW))
```
Table B2 gives sample values of the wet-element temperature $T_w(°C)$, calculated by this segment for a wet-element overall diameter of 4.5 mm and an effective airspeed of 4.5 m/s. They are for pressures of 700 and 1000 hPa and various dry-element temperatures and relative humidities.

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>Pressure (hPa)</th>
<th>Relative Humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>10</td>
<td>1000</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>(-2.11)</td>
</tr>
<tr>
<td>20</td>
<td>1000</td>
<td>5.44</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>2.81</td>
</tr>
<tr>
<td>30</td>
<td>1000</td>
<td>10.09</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>7.02</td>
</tr>
<tr>
<td>40</td>
<td>1000</td>
<td>14.13</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>10.68</td>
</tr>
<tr>
<td>50</td>
<td>1000</td>
<td>17.66</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>13.88</td>
</tr>
</tbody>
</table>

B3. The subroutine PEBET, which appears in both of the above segments, and which gives the saturation vapour pressure of pure water PE (in Pa) and its temperature derivative BET (in Pa/K), each as a function of the temperature T (in K), may be written as follows.

```
SUBROUTINE PEBET (T,PE,BET)
C1 = - 6.0951748E3
C2 = 2.116173595E1
C3 = - 2.7222404E - 2
C4 = 1.6840790E - 5
C5 = 2.4505058
W1 = C1/T+C2+[T*(C3+T*C4)+C5*ALOG(T)]
W2 = -C1/(T*T)+(C3+2.0*C4*T)+C5/T
PE = EXP(W1)
BET = PE+W2
END
```

Some sample values of the saturation vapour pressure $e_s$ (hPa) and its temperature derivative $\beta$ (hPa/K) are given in Table B3.
Table B3. Sample Values of the Saturation Vapour Pressure of Pure Water $e_s$ (hPa) and its Temperature Derivative $\beta$ (hPa/K), for a Range of Temperatures $T$ (°C)

<table>
<thead>
<tr>
<th>$T$ (°C)</th>
<th>$e_s$ (hPa)</th>
<th>$\beta$ (hPa/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>6.1121</td>
<td>0.44400</td>
</tr>
<tr>
<td>10</td>
<td>12.279</td>
<td>0.82264</td>
</tr>
<tr>
<td>20</td>
<td>23.385</td>
<td>1.4484</td>
</tr>
<tr>
<td>30</td>
<td>42.452</td>
<td>2.4366</td>
</tr>
<tr>
<td>40</td>
<td>73.813</td>
<td>3.9347</td>
</tr>
<tr>
<td>50</td>
<td>123.45</td>
<td>6.1247</td>
</tr>
<tr>
<td>60</td>
<td>199.33</td>
<td>9.2233</td>
</tr>
</tbody>
</table>
APPENDIX C

Effect of Extraneous Radiation on Measurements made with the Reference Psychrometer in the Field

C1. Introduction

By far the most important effect of the radiation incident on the reference psychrometer arises from the direct incidence of scattered solar radiation and terrestrially emitted thermal radiation on the wet and dry elements. Of course, no direct sunlight is allowed to fall on the entrance of the instrument. The effect of the extraneous radiation was estimated in 1969 in Appendix IV of the Final Report of the Working Group on Hygrometry established by CMO IV, and again in 1973 by Polland of the British Meteorological Office. The two estimates were broadly consistent.

In this appendix, measurements are reported which yield values for the radiation errors to be expected when the reference psychrometer is used to determine the relative humidity and the air temperature. They have been made in Sydney, Australia, in mid-winter and mid-summer. To make the measurements, the reference psychrometer was operated in a modified mode at a height of approximately 1.3 metres above a level, mown, grassed area, which resembles a playing field and is bordered by small trees.

C2. Nature of the Radiation

The radiation incident on the elements may be regarded as made up of two components, one the scattered solar radiation, and the other the radiation thermally emitted by the ground, by surrounding surfaces, by clouds, by atmospheric haze, and by atmospheric water vapour. These components were referred to by Polland as respectively the short-wave radiation and the long-wave radiation. They are of the same order of intensity. Less than 1% of the energy of the short-wave radiation lies at wavelengths above, and less than 0.1% of the long-wave radiation at wavelengths below 3 μm. Therefore it is possible in practice not only to construct a surface which reflects most of both the components and a surface which absorbs almost all of both, but also a surface which reflects most of the scattered solar radiation while absorbing almost all the terrestrially emitted radiation.

C3. Method

C3.1 The Elements

Elements consisting basically of stainless-steel tubes 4.0 mm in outside diameter and 0.1 mm in wall thickness were prepared with the following surfaces:

<table>
<thead>
<tr>
<th>Surface</th>
<th>Designation of element</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polished stainless steel, aluminized</td>
<td>A (for aluminized)</td>
</tr>
<tr>
<td>Stainless steel, blackened</td>
<td>B (for blackened)</td>
</tr>
<tr>
<td>Polished stainless steel, aluminized and lacquered</td>
<td>L (for lacquered)</td>
</tr>
</tbody>
</table>

For element A, the highly polished stainless-steel surface was coated with aluminium by vacuum deposition. It then had a bright, specularly reflecting finish. The surface of element B was prepared by coating the unpolished surface with a matt-black enamel. The surface of element C was first
prepared like that of element A, and then given a coating of acrylic lacquer (Dulon Ultra Clear) approximately 0.2 mm thick.

The spectral absorptances of the three types of surfaces were measured with flat specimens using a Cary spectrophotometer for the wavelength range of 0.33 to 2.0 μm and a Beckman spectrophotometer for the range 1.0 to 15 μm. The absorptance of each surface was then calculated for the solar spectrum and for the spectrum of the terrestrial radiation, taken, for this purpose, to be blackbody radiation corresponding to a temperature of 300K. Denoting the absorptance of element A for the solar radiation by $\varepsilon_{AS}$ and for the terrestrial radiation by $\varepsilon_{AT}$, and using analogous symbols for the other elements, the results may be written

$$
\begin{align*}
\varepsilon_{AS} &= 0.14 ; & \varepsilon_{AT} &= 0.03 \\
\varepsilon_{BS} &= 0.98 ; & \varepsilon_{BT} &= 0.98 \\
\varepsilon_{LS} &= 0.19 ; & \varepsilon_{LT} &= 0.98 
\end{align*}
$$

Element A has the type of surface normally to be used for the dry element.

Measurements for the wet, cotton-sleeve covered surface of the normally constituted reference psychrometer were made as above for the solar radiation, and by a special method involving a thermal source for the terrestrial radiation, the resulting absorptances being

$$
\varepsilon_{WS} = 0.59 ; & \; \varepsilon_{WT} = 0.98
$$

C3.2 The Procedure

For each set of conditions in the field, continuous recordings were made of the temperature difference of elements A and B mounted in the reference psychrometer in the place of the usual wet and dry elements, and similarly also of the temperature difference of elements A and L. During the recordings, air was drawn through the instrument at a controlled rate in the usual manner.

At the same time, measurements were made of a number of parameters which defined the conditions. However, of these, only the orientation of the psychrometer and the condition of the sky as determined by visual observation have been needed for what follows.

C4. Analysis

Let $(\Delta T)_S$ be the rise in temperature which a (hypothetical) perfectly black wet element would experience in the instrument if only the scattered solar radiation were present, and let $(\Delta T)_T$ be the corresponding rise if only the terrestrial radiation were present. Then the actual temperature rise of element A is

$$
(\Delta T)_A = \left( \frac{L}{h} \right) (\varepsilon_{AS}(\Delta T)_S + \varepsilon_{AT}(\Delta T)_T), \quad (C1)
$$

where $h$ is the total surface heat-transfer coefficient of the perfectly black element, and $h_A$ that of element A.

The coefficients $h$ and $h_A$ each comprises a convective part, and a radiative part which represents the exchange of radiation between the element and surfaces of the instrument itself. They differ only slightly, because the convective component, which is the same for each element, is dominant. Equations analogous to (C1) may be written for elements B and L. Now, numerical tests have shown that the present results are only slightly changed if the differences between $h$, $h_A$, $h_B$, and $h_L$ are neglected, so that the $h$'s disappear from the equations. Therefore, for present purposes we will make this simplification.

If the measured temperature difference between A and B is denoted by $(\delta T)_{BA}$, then, subtracting (C1)
APPENDIX C

From the corresponding equation for element B, we obtain

\[(\delta T)_{B,A} = (e_{B,S} - e_{A,S})(\Delta T)_S + (e_{B,T} - e_{A,T})(\Delta T)_T \]  \hspace{1cm} (C2)

or, numerically,

\[(\delta T)_{B,A} = 0.84(\Delta T)_S + 0.95(\Delta T)_T \]  \hspace{1cm} (C3)

Analogously,

\[(\delta T)_{L,A} = 0.05(\Delta T)_S + 0.95(\Delta T)_T \]  \hspace{1cm} (C4)

Solving (C3) and (C4), we obtain

\[(\Delta T)_S = 1.27[(\delta T)_{B,A} - (\delta T)_{L,A}] \]  \hspace{1cm} (C5)

and

\[(\Delta T)_T = 1.12(\delta T)_{L,A} - 0.07(\delta T)_{B,A} \]  \hspace{1cm} (C6)

Equations (C5) and (C6) allow \((\Delta T)_S\) and \((\Delta T)_T\) to be calculated from the experimental results for any particular set of conditions.

As the normal dry element of the reference psychrometer has the same surface as element A, then, for the same particular set of conditions, the extraneous radiation would raise its temperature by the amount given by (C1), or, numerically, by

\[(\Delta T)_A = 0.14(\Delta T)_S + 0.03(\Delta T)_T \]  \hspace{1cm} (C7)

This can be evaluated using the values of \((\Delta T)_S\) and \((\Delta T)_T\) given by (C5) and (C6).

If the normal wet cotton-sleeve covered element were in the psychrometer for the particular set of conditions, the extraneous radiation would raise its temperature by an amount which is a little more difficult to calculate, because \(h\) and \(h_w\) differ considerably. Because of the effect of the evaporation process, the effective total heat-transfer coefficient \(h_w\) is \(j\) times the value which would occur if evaporation did not take place, \(j\) being given approximately by

\[j = 1 + \frac{p}{A\beta}, \]  \hspace{1cm} (C8)

where \(A\) is the psychrometer coefficient, \(p\) is atmospheric pressure, and \(\beta\) is the rate of change of the saturation vapour pressure of water with temperature at the wet-element temperature. Equation (C8) is the same as equation (10) of the text with \(f_s\) put equal to unity. It should be noted that \(j\) depends on the wet-element temperature, and hence on the temperature and humidity. We therefore have

\[(\Delta T)_w = \frac{1}{j}[e_{w,S}(\Delta T)_S + e_{w,T}(\Delta T)_T] \]  \hspace{1cm} (C9)

or numerically,

\[(\Delta T)_w = \frac{1}{j}[0.59(\Delta T)_S + 0.98(\Delta T)_T] \]  \hspace{1cm} (C10)

The values of \((\Delta T)_A\) and \((\Delta T)_w\) calculated from (C7) and (C10) are the radiation errors in the observed dry- and wet-element temperatures respectively. The corresponding error in the derived relative humidity can be calculated using the psychrometer equation. It can be calculated for the air
temperature and humidity which actually accompanied the particular radiation conditions, or for any
temperature and humidity hypothetically regarded as accompanying those conditions. In the latter
case, \( j \) must be evaluated for the hypothetical temperature and humidity.

C5. Measurements

Experiments were carried out between 9.00am and 3.00pm on a number of days in approximately mid-
winter and mid-summer. Conditions involving a clear sky, a hazy sky or sky dotted with isolated
clouds, and complete cloud cover were included for each season. Each experiment involved the
continuous recording of \( (\delta T)_{BA} \) and \( (\delta T)_{LA} \) in consecutive runs until representative values could be
read from the records. (It would, of course, have been better to have recorded the two quantities
simultaneously, but only one instrument was available.) The actual temperature differences were
thereby obtained well within \( \pm 0.01^\circ C \). Each experiment further involved doing this for three
orientations of the instrument, in which

(a) the elements viewed only the sky (elevation 45\(^\circ\)),
(b) the instrument was horizontal, and
(c) the elements viewed only the ground (elevation -35\(^\circ\)).

The azimuth of the direction of the instrument was more or less opposite to that of the sun. There
were 33 experiments in all.

Although the air temperature was about 30\(^\circ\)C in summer, as compared with about 15\(^\circ\)C in winter,
there is no significant difference between the values of \( (\Delta T)_S \) and \( (\Delta T)_T \) for the two seasons.
Accordingly, the results for the two seasons have been lumped together for purposes of their analysis.

C6. Resulting Values of \( (\Delta T)_S \) and \( (\Delta T)_T \)

C6.1 Instrument Directed Skywards

Both for clear-sky conditions and conditions of a hazy sky or sky dotted with isolated clouds, \( (\Delta T)_S \)
and also \( (\Delta T)_T \) varied from about -0.3\(^\circ\)C to +0.3\(^\circ\)C. It would appear that the scattering ability of an
apparently clear sky varies over a considerable range. With complete cloud cover, only positive values
of \( (\Delta T)_S \) were encountered, again ranging up to about 0.3\(^\circ\)C, while values of \( (\Delta T)_T \) ranged from about
-0.07\(^\circ\)C to +0.2\(^\circ\)C. However, as cloud temperature varies considerably with cloud height, \( (\Delta T)_T \) might
be expected sometimes to attain considerably larger negative values.

C6.2 Instrument Directed Groundwards

In this case, a few very small negative values of \( (\Delta T)_T \) were encountered, but otherwise the values of
\( (\Delta T)_S \) and \( (\Delta T)_T \) were positive. Also the values for total cloud cover were generally smaller than
those for the other conditions. The values of \( (\Delta T)_S \) for all sky conditions ranged up to about 0.3\(^\circ\)C
and those of \( (\Delta T)_T \) up to about 0.2\(^\circ\)C.

C6.3 Instrument Horizontal

The results were intermediate between those for the skywards and groundwards orientations, as is to
be expected.

C7. Corresponding Errors in the Relative Humidity and Temperature

The individual values of \( (\Delta T)_S \) and \( (\Delta T)_T \) obtained from each experiment, which are naturally
correlated, have been used to calculate the corresponding radiation errors that would occur in the
relative humidity and air temperature given by the normally constituted reference psychrometer. This
APPENDIX C

has been done for a temperature of 20°C and relative humidities of respectively 20, 50 and 80%. The resulting values take into account the correlation between $ΔT_S$ and $ΔT_T$.

The relative-humidity errors, averaged over all sky conditions, are given in Table C1. The table also gives the standard deviations of the values averaged. The errors for the three separate sky conditions are given in Table C2.

A comparison of Table C1 with Table C2 shows that the small average error values in the first table for direction of the instrument towards the sky do not represent a consistently low error but a favourable average over sky conditions. For this reason, the standard deviation is more a measure of variation than a guide to the probabilities of values.

The values in Table C2 show that relatively large radiation errors can occur not only when the instrument is directed towards the sky, but also when it is directed towards the ground. However, regardless of the sky conditions the error for the horizontal position is intermediate between those for the other positions. Further it is considerably smaller in magnitude than the larger of those for the other positions, and is associated with the smallest standard deviation. Therefore, as the effect of the sky conditions is to be ignored in using the instrument, the horizontal position is distinctly preferable for relative humidity measurement.

Because the smallness of the radiation error in the relative humidity when the instrument in horizontal obviously depends on the dry and especially the wet element being able to 'see' both the sky and the ground, a conclusion as to the magnitude of the error likely in practice must be drawn in a conservative manner. Looking at the last line in Table C2, we see that the values do not vary much from one sky condition to another. Here we will firstly adopt the largest values given in Table C1 for the horizontal orientation, namely 0.20% relative humidity for the average radiation error, and 0.14% relative humidity for the associated standard deviation, which occur for the lowest relative humidity.

Taking the uncertainty at the 95% confidence level to be twice the standard deviation, its value is 0.28% relative humidity. We may combine this uncertainty statistically with that which arises from the uncertainties in the wet- and dry-element temperatures and the value adopted for $A$, which amounts to 0.30% relative humidity, and so obtain a value of 0.41% relative humidity. Then, on the basis that no correction will be applied for the average radiation error, we may conservatively obtain an effective uncertainty simply by adding the magnitude of this error to the uncertainty of 0.41% relative humidity, to obtain a value of 0.61% relative humidity. However, while the value that would be obtained for temperatures higher than 20°C is less than this, the value that would be obtained for the allowed lower temperatures is slightly greater. Consequently, to obtain a general result, we round the value to 1% relative humidity.

This uncertainty is only about a third of the minimum required uncertainty for surface measurements of humidity, as estimated by Hawson (1970), and so is satisfactory for a reference standard instrument.

The results for the radiation error in the observed air temperature are more straightforward to interpret, and need no tabulation. Averaging over the different sky conditions, the mean value is about 0.025°C for each direction of the instrument. The standard deviation for direction towards the sky is 0.026°C, while that for each of the other directions is only about half this value. (There were approximately 30 experimental values for each case.) Thus, the horizontal direction, which has been seen above to be superior for relative humidity measurement, is as good as, or better than, either of the other directions as regards air-temperature measurement.

For the horizontal instrument, the average radiation error in the observed air temperature is found to be 0.026°C and the associated uncertainty to be 0.024°C. Combining the latter statistically with the uncertainty of 0.03°C contributed by the thermometry, we get a value of 0.038°C. Finally, on the basis that no correction will be applied for the average radiation error, and by analogy with the procedure followed for the uncertainty in the humidity, we conservatively add the average radiation error to this value to obtain an effective uncertainty of 0.064°C, and round this to 0.07°C. Unlike the corresponding uncertainty in the humidity, this value is approximately valid regardless of the
temperature and humidity.

The uncertainty is less than half the minimum required uncertainty for surface measurements of air temperature, as estimated by Hawson (1970), and so the reference psychrometer could serve as the reference standard for air-temperature measurement as well as for relative humidity measurement.

Above a snow covered surface, higher values of $(\Delta T)_s$ could almost certainly give rise to larger errors in the relative humidity and air temperature than found for a grassed surface. Over a bare sand surface, higher values of both $(\Delta T)_s$ and $(\Delta T)_T$ could probably give rise to larger errors.
### Table C1. Overall Average and Standard Deviation of the Radiation Error in the Derived Relative Humidity for 20°C and Relative Humidities of 20, 50 and 80%

<table>
<thead>
<tr>
<th>Instrument directed to</th>
<th>Number of experiments</th>
<th>20% r.h.</th>
<th>Standard Deviation</th>
<th>50% r.h.</th>
<th>Standard Deviation</th>
<th>80% r.h.</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>SKY</td>
<td>33</td>
<td>+0.09</td>
<td>0.41</td>
<td>+0.05</td>
<td>0.37</td>
<td>+0.01</td>
<td>0.34</td>
</tr>
<tr>
<td>GROUND</td>
<td>32</td>
<td>+0.31</td>
<td>0.20</td>
<td>+0.27</td>
<td>0.18</td>
<td>+0.23</td>
<td>0.17</td>
</tr>
<tr>
<td>HORIZON</td>
<td>27</td>
<td>+0.20</td>
<td>0.14</td>
<td>+0.15</td>
<td>0.12</td>
<td>+0.10</td>
<td>0.11</td>
</tr>
</tbody>
</table>

### Table C2. Average Radiation Error in the Derived Relative Humidity for Three Different Sky Conditions and for 20°C and Relative Humidities of 20, 50 and 80%

<table>
<thead>
<tr>
<th>Instrument directed to</th>
<th>CLEAR SKY</th>
<th>HAZE OR CLOUD</th>
<th>TOTAL CLOUD COVER</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Mean Error</td>
<td>Mean Error</td>
<td>Mean Error</td>
</tr>
<tr>
<td></td>
<td>20% r.h.</td>
<td>50% r.h.</td>
<td>80% r.h.</td>
</tr>
<tr>
<td>SKY</td>
<td>-0.16</td>
<td>-0.16</td>
<td>-0.16</td>
</tr>
<tr>
<td>GROUND</td>
<td>+0.45</td>
<td>+0.40</td>
<td>+0.36</td>
</tr>
<tr>
<td>HORIZON</td>
<td>+0.17</td>
<td>+0.13</td>
<td>+0.09</td>
</tr>
<tr>
<td></td>
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