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PEOPLE'S DEMOCRATIC REPUBLIC OF ALGERIA

وزارة التعليم العالي و البحث العلمي
جامعة محمد بوضياف بالمسيلة
كلية التكنولوجيا
قسم الهندسة الكهربائية

MINISTRY OF HIGHER EDUCATION AND
SCIENTIFIC RESEARCH
MOHAMED BOUDIAF UNIVERSITY OF M'SILA
FACULTY OF TECHNOLOGY
DEPARTMENT OF ELECTRICAL ENGINEERING

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شهادة إدارية

بخصوص مطبوعة الدروس الخاصة بالأستاذ

زميت عبد الرحيم

بناءً على محضر اللجنة العلمية لقسم الهندسة الكهربائية تحت رقم: 365/ق.هـ.ك/2024 المنعقد بتاريخ 06 نوفمبر 2024 والمتضمن تعين الخبراء: الأستاذ حريزي عبد الغفور أستاذ محاضر -أ- بجامعة المسيلة الأستاذ روابحي رياض أستاذ محاضر –أ- بجامعة المسيلة، والأستاذ دايلي ياسين أستاذ محاضر –أ- بجامعة سطيف 01 وذلك لتقييم مطبوعة الدروس الخاصة بالأستاذ زميت عبد الرحيم أستاذ محاضر "أ" بقسم الهندسة الكهربائية لجامعة المسيلة تحت عنوان :

" Capteurs et mesures dédiés aux systèmes à énergies renouvelables "

مطبوعة دروس مكتوبة باللغة الإنجليزية تحت عنوان:

" Sensors and measurements dedicated to renewable energy system"

وبعد إطلاع رئيس اللجنة العلمية ورئيس القسم على التقارير الواردة و التي كانت كلها ايجابية، وعليه فإن اللجنة لا ترى مانعا أن تتخذه سندا في تدريس طلبة السنة الثانية ماستر طاقات متجددة في الكهروتقني، شعبة طاقات متجددة ، ميدان علوم و تكنولوجيا و أن تعتمد في أي تقييم للمسار العلمي للأستاذ المعني.

رئيس اللجنة العلمية
أ .د بوقرة عبد الرحمان

رئيس اللجنة العلمية
قسم الهندسة الكهربائية

رئيس القسم

رئيس قسم
الهندسة الكهربائية

دفداف المبروك

ملاحظة: سلمت هذه الشهادة للمعني(ة) لاستعمالها في حدود ما يسمح به القانون.

الجمهورية الجزائرية الديمقراطية الشعبية
People's Democratic Republic of Algeria
وزارة التعليم العالي و البحث العلمي
Ministry of Higher Education and Scientific Research

Mohamed Boudiaf University of M’sila
Faculty of Technology
Department of Electrical Engineering

جامعة محمد بوضياف - المسيلة
كلية التكنولوجيا
قسم : الهندسة الكهربائية

Course

Sensors and Measurements Dedicated to Renewable Energy System

2^{nd} year Master in Renewable Energies in Electrotechnics

Directed by :
Dr. ZEMMIT Abderrahim
Lecturer in the Department of Electrical Engineering

Academic year : **2023-2024**

Objectives of the Course

The objective of this course is to provide students with general knowledge of metrology as applied to renewable energy (RE) systems, with a particular focus on photovoltaic (PV), wind, and fuel cell (FC) technologies. The course aims to familiarize students with various types of physical quantities relevant to these systems, including meteorological, electrical, and energy parameters. Students will explore different types of sensors, measurement instruments, and characterization techniques used by professionals in the field. Special attention is given to the measurement of temperature, solar radiation, humidity, wind speed and direction, and atmospheric pressure. Additionally, the course introduces standards related to meteorological instruments, which are essential for ensuring reliable and accurate data. This knowledge is crucial for engineers involved in the design, monitoring, and optimization of RE systems. A recommended prerequisite for this course is prior knowledge of electrical sensors and measurement techniques.

Recommended prior knowledge: Electrical sensors and measurement techniques.

Course Content

The course is structured into seven chapters, each covering essential aspects of measurement and instrumentation in the context of renewable energy systems. The content is as follows:

- **Chapter 1: Introduction to Meteorological Instruments**
  Overview of key instruments used in meteorological measurements, their principles, and applications in RE systems.
- **Chapter 2: Measurement of Temperature**
  Techniques and sensors used to measure ambient and system-related temperatures.
- **Chapter 3: Measurement of Sunshine Duration and Solar Radiation**
  Methods for measuring solar irradiance and sunshine hours, crucial for PV system performance evaluation.
- **Chapter 4: Measurement of Humidity**
  Instruments and processes used to monitor air humidity and its impact on energy systems.
- **Chapter 5: Measurement of Surface Wind**
  Measurement of wind speed and direction, essential for wind energy applications.
- **Chapter 6: Measurement of Atmospheric Pressure**
  Tools and methods for pressure monitoring and its relevance in system analysis.
- **Chapter 7: Standards for Meteorological Instruments**
  Overview of international and industry standards for accuracy and calibration of instruments.

Assessment Mode: Summative Evaluation

Chapter 1: Introduction to Meteorological Instruments

CONTENTS

Chapter 1: Introduction to Meteorological Instruments

1.1 Definitions

This section defines terminology related to meteorological instruments.

1.1.1 Instrument Standards

The term "standard" and other similar expressions refer to the various instruments, methods and scales used to establish the uncertainty of measurements. The Guide to Meteorological Instruments and Methods of Observation (CIMO Guide (WMO-No. 8)) provides definitions as follows:

(Measurement) standard: A material measure, measuring instrument, reference material or measuring system intended to define, realize, conserve or reproduce a unit or one or more values of a quantity to serve as a reference

International standard: A standard recognized by an international agreement to serve internationally as the basis for assigning values to other standards of the quantity concerned

National standard: A standard recognized by a national decision to serve, in a country, as the basis for assigning values to other standards of the same quantity

Primary standard: A standard that is designated or widely acknowledged as having the highest meteorological qualities and whose value is accepted without reference to other standards of the same quantity

Secondary standard: A standard whose value is assigned by comparison with a primary standard of the same quantity

Reference standard: A standard, generally having the highest meteorological quality available at a given location or in a given organization, from which the measurements taken there are derived

Working standard: A standard that is used routinely to calibrate or check material measures, measuring instruments or reference materials

Notes:
1. A working standard is usually calibrated against a reference standard.
2. A working standard used routinely to ensure that measurements are being carried out correctly is called a “check standard”.

Transfer standard: A standard used as an intermediary to compare standards

Travelling standard: A standard, sometimes of special construction, intended for transport between different locations

Collective standard: A set of similar material measures or measuring instruments fulfilling, by their combined use, the role of a standard (example: the World Radiometric Reference)

Traceability: A property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties

Calibration: The set of operations which establish, under specified conditions, the relationship between values indicated by a measuring instrument or a measuring system, or values represented by a material measure, and the corresponding known values of a measurand (the physical quantity being measured)

1.1.2 Instrument Accuracy

Terminology related to the accuracy of measurements and the expression of measurement uncertainty is defined here.

True value: A value consistent with the definition of a given particular quantity

Note: This is a value that would be obtained by a perfect measurement. However, true values are by nature indeterminate.

Accuracy of measurement: The closeness of the agreement between the result of a measurement and the true value of the measurand

Note: Accuracy is a qualitative concept.

Repeatability (of measurement results): The closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement

Reproducibility (of measurement results): The closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement

Uncertainty (of measurement): A variable associated with the result of a measurement that characterizes the dispersion of values that could be reasonably attributed to the measurand

Error (of measurement): The result of measurement minus the true value of the measurand

Note: Since a true value cannot be determined, in practice a conventional true value is used.

Deviation: The value minus its conventional true value

Random error: The result of a measurement minus the mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions

Notes:

1. Random error is equal to error minus systematic error.
2. Because only a finite number of measurements can be made, it is possible to determine only an estimate of random error.

Systematic error: The mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions minus the true value of the measurand

Notes:

1. Systematic error is equal to error minus random error.
2. Like true value, systematic error and its causes cannot be completely known.

Correction: A value added algebraically to the uncorrected result of a measurement to compensate for systematic error

1.1.3 Instrument Characteristics

Other instrument properties that must be understood when considering accuracy are described here.

Sensitivity: The change in the response of a measuring instrument divided by the corresponding change in the stimulus (see Section 1.2.2.2)

Note: Sensitivity may depend on the value of the stimulus.

Discrimination: The ability of a measuring instrument to respond to small changes in the value of the stimulus

Resolution: A quantitative expression describing the ability of an indicating device to distinguish meaningfully between closely adjacent values of the quantity indicated

Hysteresis: The property of a measuring instrument whereby its response to a given stimulus depends on the sequence of preceding stimuli

Stability (of an instrument): The ability of an instrument to maintain constant meteorological characteristics with time

Drift: The slow variation with time of the meteorological characteristics of a measuring instrument.

Response time: The time interval between the instant at which a stimulus is subjected to a specified abrupt change and the instant at which the response reaches and remains within specified limits around its final steady value (see Section 1.2.2.3)

Lag error: The error that a set of measurements may possess due to the finite response time of the observing instrument

1.2 Fundamentals of Measurement

1.2.1 Measurement Error

The term "measurement" is used to describe the process or result of recording specific values, and may also be called an "observation" in meteorological contexts. Devices used to objectively indicate meteorological variables such as air temperature and precipitation amounts are called "meteorological instruments," or simply "instruments." All measuring instruments can be classified as analogue or digital according to the way they indicate information.

Analogue measuring instruments provide indications in continuous analogue form. The value of the measured variable is read by the observer from a suitably graduated scale.

Digital measuring instruments display the value of the measured quantity in a discrete numerical form as a value on a digital display. This value can be printed out or processed in a computer environment.

All measurements are accompanied by some degree of error. Errors in measurement stem from accumulated discrepancies related to traceability that occur in calibration operations in addition to those caused by observation conditions such as the influence of solar radiation when air temperature is measured. Errors also are classified as either systematic or random according to the processes of their occurrence. If the observer reads out a value from a scale, artificial errors caused by the observer are included.

Systematic errors can sometimes be eliminated through post-measurement correction, and include instrumental errors as well as those that cannot be completely eliminated, such as irregular errors caused by drift due to deterioration of a material's elastic properties or by friction. The level of systematic error can be minimized through regular comparison with or calibration against a reference standard.

Random errors are caused by factors such as noise from the instrument itself, and are difficult to eliminate.

Artificial errors include bias caused by the observer's propensities or carelessness in reading the scale. They can be considerably reduced if the observer takes care in reading measurements.

Although errors in measurement are unavoidable, they should be minimized through regular maintenance, monitoring of observed values and the like.

In addition to these errors, the environment of the observation site also affects observations. This effect is discussed in Section 1.5.4.

1.2.2 Instrument Characteristics

1.2.2.1 Accuracy

As described in the previous section, all measurements are inevitably accompanied by some degree of error. In many cases, the frequency distribution of the difference in the values obtained from an instrument with reference to the true values obtained from a reference standard is as shown in Figure 1.1.

In this figure, T is the true value obtained from the standard, O is the mean value observed with the instrument, and σ_0 is the standard deviation of the values obtained from the instrument under consideration. In this case, the following characteristics apply:

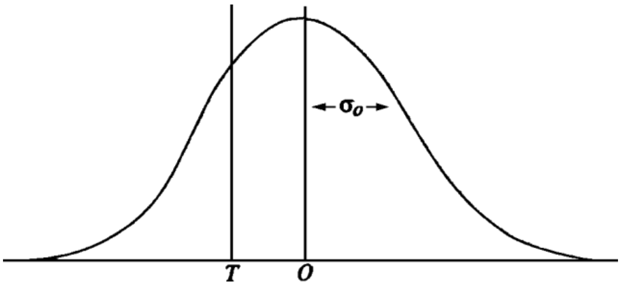


Figure 1.1 Distribution of data in instrument

O – T: systematic error

σ_0 : measurement precision indicating dispersion

The accuracy of this instrument is expressed by (O - T) ± f (σ_0), where f is the probability function. For a series of measurements that would produce an error distribution with standard deviation σ_0, this probability function indicates the likelihood of a value of random error occurring for an arbitrary measurement.

An instrument with a low level of systematic error and dispersion (i.e., low deviation) and high precision is an accurate instrument, which is highly desirable.

Accuracy is a qualitative representation, and its quantitative representation is uncertainty. It is preferable to represent accuracy in terms of uncertainty. In the CIMO Guide, "an accuracy of ± x" is sometimes used, but this should actually read "an uncertainty of ± x at a 95% confidence level."

1.2.2.2 Sensitivity

When a measured value changes in response to a change in the target of measurement, the ratio expressing these changes represents a value called sensitivity. For electric measuring instruments, this corresponds to the ratio of the output signal to the input signal, and is known as the gain. The term "gain" is also used in the same way for general measuring instruments. For example, the sensitivity of a mercury-in-glass thermometer is represented as the ratio of change in the height of the mercury column (output) for a temperature change of 1°C (input). An instrument with a large value for this ratio has high sensitivity.

To facilitate measurement and maximize its accuracy, it is necessary to select an instrument with an appropriate level of sensitivity for the purpose of the measurement. Instruments with high sensitivity tend to have a narrow range of measurement.

1.2.2.3 Response and Time Constant

To measure meteorological variables using an instrument, the surrounding environment and the sensor of the instrument need to be in equilibrium. The temperature of the ambient air, for example, must be the same as the temperature of the mercury in a mercury-in-glass thermometer. If there is a sudden change in the measured quantity, a certain length of time (known as the settling time) is needed to allow a return to equilibrium. This period is called the response time of the instrument.

Meteorological measuring instruments are classified as either first-order or second-order units according to their dynamic behavior during the process through which equilibrium is attained.

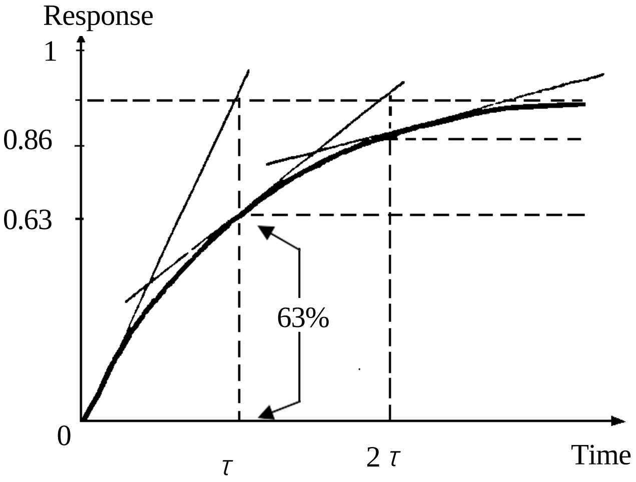


Figure 1.2 Response of a first-order measuring instrument

The response of simple instruments such as thermometers and hygrometers to a step change takes the form shown in Figure 1.2. When a step change is given, the change in output is proportional to the difference between the input (the given forcing function value) and the output. The output approaches the forcing function value rapidly at first, and then gradually. Instruments with such a response are called first-order measuring instruments.

This delay of output in response to input is represented by a time constant (τ in the figure), which is defined as the time taken for the output to reach about 63% of its forcing function value. Approximately 86% of this value is reached by 2τ, and about 99% by 5τ.

The time constant of an anemometer varies almost inversely with wind speed; that is, it is large when the wind speed is low and vice versa. Accordingly, the product of wind speed and the time constant is almost constant, and has a dimension of length known as the response length. The response of an anemometer is represented by the response length.

The definition of the time constant described above is not applied to wind vanes, which oscillate around the direction of airflow before stabilizing. The response of such instruments to a step change in input takes the form shown in Figure 1.3. These instruments are known as second-order units, and their response to a step change oscillates with amplitudes and periods that are functions of the damping ratio (ξ), defined as the ratio of the actual damping of the instrument to the critical damping, which produces no overshoot.

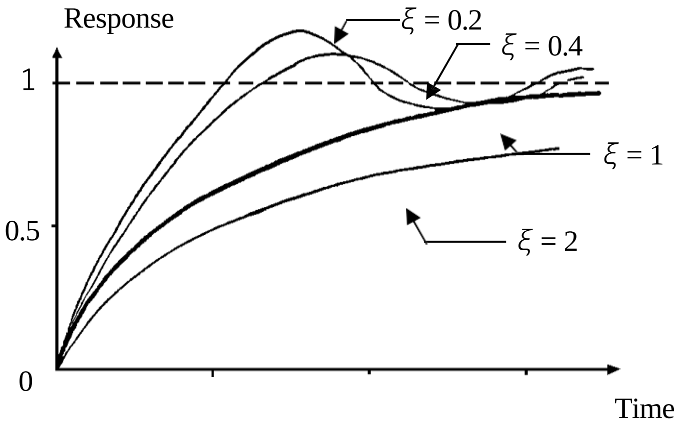


Figure 1.3 Response of a second-order measuring

If ξ is unity, the unit behaves similarly to a first-order measuring instrument; that is, the output approaches its forcing function value rapidly at first and then gradually. If ξ is less than unity, the damping is small (known as underdamping); the output goes beyond the forcing function value and then gradually converges toward it while oscillating around it. The overshoot is small if the value of ξ is close to unity. If ξ is larger than unity, the damping is too strong (known as overdamping); the output approaches the forcing function more slowly, and the response is duller than that in the case of critical damping.

The World Meteorological Organization (WMO) recommends an appropriate damping ratio ξ of between 0.3 and 0.7 so that wind vane overshoot is not excessive but a reasonably short response time is maintained.

It is necessary to select an instrument with an appropriate time constant and damping ratio for the purpose of the measurement. At the same time, there is also a need to determine appropriate methods for processing data such as the sampling interval and the averaging time according to the time constant. It would be pointless, for example, to obtain data with a sampling interval shorter than the time constant of the instrument.

The WMO recommends the use of instruments with a time constant of around 20 seconds and the adoption of an averaging time of more than one minute. Other values are also recommended for the measurement of wind speed; these will be discussed in Chapter 4.

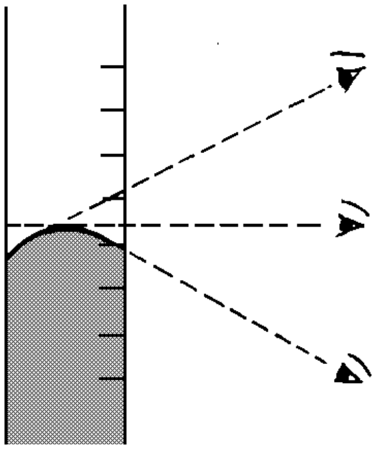


Figure 1.4 Parallax error

1.2.3 Scale Reading

The recent proliferation of automatic instruments has diminished the need for scale readings by observers. However, liquid-in-glass thermometers and precipitation gauges are still widely used, and aspirated psychrometers and mercury barometers are adopted as reference standards. As these instruments have to be read by an observer, a number of points should be kept in mind when making direct readings.

As graduated scales on mercury-in-glass thermometers and mercury barometers stand slightly apart from the mercury column itself, a reading error (known as parallax error) will occur if the observer's eyes are not in the appropriate position, as shown in Figure 1.4; the height of the eyes must be level with the top of the mercury column. In the case of instruments equipped with a mirror on the scale plate (such as aneroid barometers), the observer must read the scale with the eyes in the correct position so that the pointer coincides with its mirror image.

It is sometimes necessary to read down to 1/10 or 1/5 of a scale division. In such cases, errors can occur due to the intervals of scale divisions, the thickness or color of scale marks or observer fatigue. It is also known that reading biases arise as a result of personal propensities. It is therefore important that the observer knows his/her own propensities.

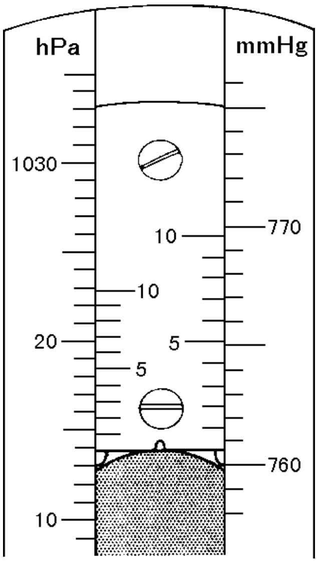


Figure 1.5 A vernier scale

1.2.3.1 Verniers

A vernier scale helps the observer to eliminate errors that may occur in reading tenths of a scale division. Some meteorological instruments (such as Fortin mercury barometers) have a vernier that allows reading to a tenth or a twentieth of the scale division. Verniers are also used in vernier calipers and micrometers.

A vernier scale is divided into 10 or 20 equal parts of 19 divisions of the main scale, or 10 equal parts of 9 divisions of the main scale. When a vernier scale is divided into 10 equal parts of 9 divisions of the main scale as shown Figure 1.5, the relationships governing the length of a single division on the main scale S and that of the vernier scale V are expressed as follows:

$$10\mathrm{V} = 9\mathrm{S}, \qquad \mathrm{S} - \mathrm{V} = \frac{1}{10}\mathrm{S}\,.$$

The difference between a division on the main scale and one on the vernier scale is one tenth of a division on the main scale. If the *n*th mark on the vernier scale aligns with a mark on the main scale, the 0 mark on the vernier lies at n/10 of a division of the main scale.

1.3 Accuracy Required for Observation and Sources of Errors

Taking air temperature as an example to discuss how errors arise, sources in individual measurements are as follows:

(a) Errors in international, national and working standards and in comparisons made between them. However, these may be negligible in meteorological applications.

(b) Errors in comparisons made between standards and operational instruments in a climatic chamber or a laboratory. Such errors are small if the operating conditions are appropriate (for example, ± 0.1K uncertainty at a 95% confidence level including the type of errors in (a) above), but can easily become large depending on the skill of the operator and the quality of the facility.

(c) Errors can occur in each measurement due to instrument characteristics; these include errors stemming from incomplete correction for nonlinearity and secular changes due to drift, as well as those caused by fluctuating characteristics of repeatability or reproducibility.

(d) Errors may arise as a result of temperature differences between the air around a thermometer and that within a screen or ventilated shelter. Such errors are small if there is appropriate ventilation, but become large otherwise.

(e) Errors can be caused by sunshine-related temperature differences between the air within a screen or ventilated shelter and the ambient air. Although such errors are small if the screen or ventilated shelter is designed appropriately, the difference in extreme environments may be more than 3°C between ventilated shelters with and without effective sunshine shielding.

(f) Considerable errors may arise if the site is not typical of the surrounding environment, such as if there are heat sources or sinks (e.g., buildings, roads with heavy traffic, land-water boundaries, etc.) nearby.

Of these error sources, (a) to (c) stem from the characteristics of instruments themselves. These types of error must be minimized through appropriate instrument selection and calibration.

The effects of (d) to (f) can be limited if instruments are installed at appropriate sites and operated with care. Otherwise very large errors may arise.

1.4 General Requirements for Instruments

Major requirements for meteorological instruments are accuracy, reliability, convenience of operation and maintenance, simplicity of design and durability.

It is important that the accuracy of an instrument is kept constant over a long period. An instrument whose accuracy is relatively low but can be maintained is better than one with initially high accuracy that deteriorates over time. Accordingly, the following factors should be considered in instrument selection:

(a) An instrument with appropriate accuracy should be selected according to the purpose of the observation. In general, high-accuracy instruments are expensive and difficult to handle.
(b) The instrument's accuracy should be stable over a long period to minimize the need for maintenance work.
(c) It should be easy to identify the sources of errors and eliminate them.

Calibration before instrument installation and after overhaul (including repairs) is necessary to correct observation data and maintain high-accuracy observation.

Most meteorological instruments are in continuous use, meaning that immediate repair or adjustment is not always possible at some sites. Accordingly, a simple, strong structure along with easy operation and maintenance are important factors. A robust structure is especially important for instruments installed outdoors. Although the equipment used for such units may be expensive, they offer better observation results at lower cost in the long run.

1.5 Maintaining Accuracy

1.5.1 Maintenance

Sensors of meteorological instruments (except those of barometers) are installed outdoors, and are exposed to rain, wind and sunshine. Regular maintenance is therefore necessary to achieve stable operation and obtain accurate data. Rain gauges, for example, sometimes become clogged with leaves or dirt, and defective contacts of connectors, water infiltration, strong winds or lightning frequently cause damage to instruments. In addition to regular maintenance, special maintenance also needs to be carried out after unusual stormy events.

Even if an observation environment is favorable at the time of initial installation, changes such as the growth of trees and weeds may change the observation conditions. Accordingly, necessary maintenance such as trimming and mowing during regular inspections should be carried out as appropriate.

An instrument maintenance schedule for regular inspections and part replacement should be drawn up in consideration of the inspection procedures recommended by the manufacturer.

By executing observation data quality control regularly and as frequently as possible at observation sites or data centers where observation data are collected and used, it is possible to detect problems with instruments early.

1.5.2 Comparison and Calibration

Operational instruments should be calibrated before installation against a reference standard in a climatic chamber, a wind tunnel or other such facilities. The results of calibration for correction should be prepared for use at any time for each station.

As the performance and characteristic values of an instrument change gradually over time, regular calibration should be planned. Interim calibration should be carried out in the following cases:

(a) When a change of appearance that may affect instrument performance is recognized
(b) When an instrument is repaired or adjusted
(c) When a systematic error in the observed values is recognized after comparison with other instruments of the same type
(d) When the instrument seems to exhibit a change in performance after inspection

To identify performance changes in operational instruments, on-site comparison with reference standards should be regularly carried out. The comparison interval should be determined by considering the change in performance of each instrument.

1.5.3 Handling of Instruments

This section describes common considerations for the handling of instruments.

1.5.3.1 Handling of Chemical Agents and Other Hazardous Materials

Chemical agents harmful to humans are used in some meteorological instruments as well as in accuracy verification work and maintenance. Such chemicals should be handled and stored according to the relevant instructions and any regulations issued by national authorities. In handling these chemicals, the following precautions should be noted:

(a) All individuals involved in handling should know the chemical properties of the material.
(b) Materials should be kept in well-labeled containers and stored appropriately.

Mercury – an element poisonous to humans – is often used in barometers and thermometers. It is absorbed into the body through the skin in both liquid and gaseous states, and its vapor can be inhaled. A high intake of mercury results in acute poisoning. As mercury accumulates in bones or the tissues of internal organs, even small amounts can cause chronic organ disorders and be fatal in the long term. It is therefore necessary to pay attention to the following points when handling mercury:

(a) The floor of rooms where mercury is stored or used in large amounts should be shielded and laid with an impervious covering. It must not be stored together with other chemicals, especially with ammonia or acetylene.
(b) Mercury has a relatively low boiling point of 357°C, and produces dangerous poisonous gas upon combustion. It must not be stored close to heat sources.
(c) Regular inspections of the room and staff should be carried out when mercury is handled to catch hazardous levels of mercury concentration.

1.5.3.2 Safety of Operation

Most wind vanes, anemometers, radiometers and sunshine recorders are installed in elevated locations to avoid influence from neighboring buildings and other obstacles. In designing poles or towers, footholds for routine inspections and maintenance work should be secured. Workers should be sure to prepare safety belts for these operations.

1.5.3.3 Transportation of Instruments

When a meteorological instrument is moved, it should be handled carefully so that its accuracy is not affected. Details of special considerations for mercury barometers and other instruments are described in the relevant chapters.

(a) Use a special case for transportation if available. Otherwise, a crate or similar container should be prepared. It is preferable to use the instrument container originally provided by the manufacturer. Before transportation, wrap the instrument to protect it from dust and pack with cushions to prevent breakage. Protect thermometer bulbs by placing a corrugated cardboard box around them before packing. Take care to keep the unit upright during transportation. When transporting electronic instruments or precision electrical circuits, take special care to protect them from strong shock or vibration.

(b) Fully unwind the springs of clock-driven recorders. Insert a cushion in the space above the drum-holding knob at the top of the center shaft in order to prevent vertical play of the drum. Remove the pin (with a ring) that connects the lever and the reed, and tie it to the stud. Wipe any ink from the recording pen and keep it away from the recording chart. Tie the pen arm to the pen holding lever. Reinforce the cover glass of the recorder with plywood or similar to prevent breakage.

(c) In addition to these general instructions for transportation, refer to the instructions in the manufacturer’s manual.

1.5.4 Siting and Exposure

1.5.4.1 Metadata

The accuracy of meteorological observation is affected not only by the instrument itself but also by the site, the exposure of the instrument and observation operations. Accordingly, records should be kept at each site outlining the history (metadata) of instruments and observation environments, including details such as the establishment of the observatory, the history of maintenance, calibrations and maintenance, the location of instruments and staff changes. Metadata is especially important for precipitation, wind, air temperature and other observation elements that are sensitive to the location of the instrument.

1.5.4.2 Site Selection

Meteorological observation sites should be established in locations where the observed values of meteorological elements are typical of those in the surrounding area. In general, for most meteorological observations, the site should be free from the influence of natural obstacles and artificial buildings. For precipitation, however, surrounding wind fields have an influence, making sites where obstacles effectively provide shelter from winds in all directions favorable. The environment of an observation site may change over time as trees grow and buildings are constructed nearby. Sites should be located, if possible, in a place where such influences are minimal. However, as it is difficult to find this type of ideal location for observation in most cases, it is also important to understand the influence of the environment on observation elements and to keep the metadata described above to allow evaluation of validity for observed values.

1.5.4.3 Determination of Reference Direction

Wind vanes, propeller anemometers, sunshine recorders and radiometers must be installed in an appropriate direction. As it is easiest to locate in the meridian direction, instruments are generally marked with "north" and "south" so that they may be aligned with the meridian line. Methods to determine the meridian direction are outlined below.

(a) **Method using the position of the sun**. This approach makes use of the sun’s position at the meridian hour. Although the technique provides the correct direction, it requires considerable skill to attain high accuracy, and weather conditions may limit the window of time in which it can be used.

The sun will cause a vertical object to cast a shadow indicating the exact meridian direction at the meridian hour. The longer the shadow of the object, the more easily the meridian direction can be determined, resulting in higher accuracy. Suspending a weight with a thread is the easiest and most accurate way of casting a shadow. In such cases, to keep the weight at rest, it should be ensured that the upper end of the thread is attached firmly and windbreaks are arranged to prevent the weight from swinging.

With a tripod and a conical weight, a line can be drawn by tracing the shadow of the thread at the meridian hour. As it is difficult to draw a meridian line passing through a given point on the stand on which the instrument is mounted, it should first be drawn in an appropriate position, and a line parallel to it should be transferred to the appropriate position.

Since the sun moves at a rate of 15 degrees of longitude per hour, the meridian hour at a specific observation point can be derived by proportionally dividing one hour by the longitude difference between the observation point and the central standard time site of that country. If the observation point lies to the west and the longitude difference is 10 degrees:

Time difference = 60 minutes × (10 degrees/15 degrees) = 40 minutes

The meridian hour at this point is 40 minutes past the standard-time meridian hour.

(b). **Method using a magnetic compass.** This approach is advantageous in that the meridian line can be determined easily and irrespective of weather conditions. However, determination with a compass may involve some error if there are magnetized objects or iron nearby. When measuring, it should be noted that the northern direction indicated by the magnetic needle (magnetic north) deviates from true north (a deviation known as the declination), and this deviation differs from place to place. In Japan, magnetic north deviates from 4 to 10 degrees to the west of true north.

In practice, the measurer should stand to the magnetic south of the instrument and move an angular distance equal to the declination so that the instrument comes to a position distanced by the declination from magnetic north. A line can then be drawn from the measurer’s position to the position of the instrument. This is the meridian line for the instrument.

(c). **Method using a map**. This is the simplest approach to determining the direction, and involves locating a landmark at true north or south on the map. If there are no good landmarks in these directions on the map, several other landmarks can be used and their respective azimuth angles (the angle from true north) can be derived from the map. North can be determined from these azimuth angles using a theodolite or the like.

On vernal and autumnal equinox days, the sun rises and sets in the true east and true west, meaning that ground objects can be used if they are photographed or sketched.

1.5.5 Procedure for Instrument Replacement

The influence of instrument replacement on measured values should be minimized. Accordingly, the difference in performance between the new instrument and the current one should be checked in a laboratory. If the new instrument has different characteristics, the change in observed values after replacement may be mistaken as a change in the climate around the observation site. In order to evaluate this change, the new and current instruments should be compared for at least a year before the current one is taken out of service.

Similarly, if the observation site is to be changed, it is preferable to carry out observations at both the new and old sites and compare the results.

1.5.6 Approach to Observation

Unlike physical experiments performed in laboratory environments, it is impossible to repeat meteorological observations carried out in natural conditions. Observers should therefore try to fully understand the operational conditions of their instruments and observation environments.

The use of automatic observations has recently increased, and we are apt to quickly accept indicated or recorded data. However, unlike communication apparatus and other equipment, stable operation cannot always be expected from meteorological instruments, and incorrect values are sometimes indicated. Observers should keep in mind that no instrument is perfect and pay careful attention to weather changes and data at neighboring observation sites. It is important to detect instrument faults as soon as possible.

Chapter 2: Measurement of Temperature

CONTENTS

Chapter 2: Measurement of Temperature

2.1 Definition and units

Heat balance difference of atmosphere between regions creates temperature distribution. This temperature distribution generates wind current along with cloud and rainfall phenomena. Thus, atmospheric temperature is one of the most important meteorological elements as well as wind and precipitation.

WMO recommends to measure atmospheric temperature at the height from 1.25 to 2m above ground at a representative location of region, as standard.

2.1.1 Definition of atmospheric temperature

The thermodynamic temperature is defined as one of the seven quantities (length, mass, time, electric current, thermodynamic temperature, amount of substance and luminous intensity) in the International System of Unit (SI). The definition of unit is as described below:

The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.

Temperature and temperature difference can be expressed in both Kelvin and Celsius. Relation of temperature in degree Celsius (t, unit : °C) and thermodynamic temperature in Kelvin (T, unit : K) is shown as follows. Degree Celsius is commonly used in meteorological observation.

$t/°C = T/K - 273.15$

Phase diagram of water and outline of water triple point cell is shown in Figure 2.1 and Figure 2.2.

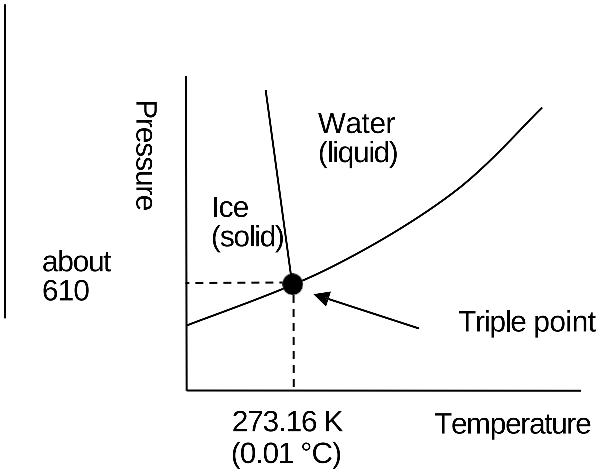


Figure 2.1 Phase diagram of water

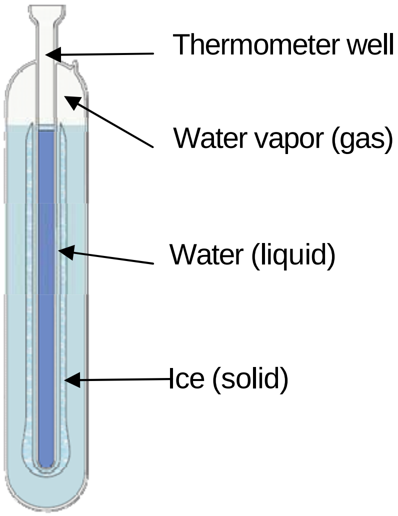


Figure 2.2 Water triple point

2.1.2 The international temperature scale

The international temperature scale is a temperature scale to accord with the results of thermodynamic temperature measurements along with the definition of thermodynamic temperature in 2.1.1 and it is defined based on several fixed points of temperature (defining fixed points) such as phase transition temperature of substance and using several types of stable thermometers. First international temperature scale was established in 1927. Since then it was revised several times to expand temperature range and improve accuracy. Currently the international temperature scale of 1990 (ITS-90) is in effect.

The ITS-90 defines the fixed points of temperature, the type of instrument along with method to interpolate in between fixed points of temperature（Table 2.1, Table 2.2）.

For the temperature range used in meteorological observation, a platinum resistance thermometer is specified as the interpolate instrument. To be a standard, an acceptable platinum resistance thermometer must be made from pure, strain-free platinum, and it must satisfy at least one of the following two relations:

$R\ (29.7646\ °C) / R\ (0.01\ °C) >= 1.11807$
$R\ (-38.8344\ °C) / R\ (0.01\ °C) <= 0.844235$
($R\ (t\ °C)$: resistance at t °C)

This determines the purity of platinum and its state of annealing.

By using the interpolation formula defined in the ITS-90, temperatures in between the fixed points of temperature can be determined from measurements obtained by a platinum resistance thermometer.

Table 2.1 Defining fixed points of the ITS-90

Number	Temperature		Substance(*1)	State(*2)
	T_{90}/K	t_{90}/°C		
1	3 to 5	-270.15 to -268.15	He	V
2	13.8033	-259.3467	e-H_2	T
3	～ 17	～ -276.15	e-H_2(or He)	V(or G)
4	～ 20.3	～ -252.85	e-H_2(or He)	V(or G)
5	24.5561	-248.5939	Ne	T
6	54.3584	-218.7916	O_2	T
7	83.8058	-189.3442	Ar	T
8	234.3156	-38.8344	Hg	T
9	273.16	0.01	H_2O	M
10	302.9146	29.7646	Ga	F
11	429.7485	156.5985	In	F
12	505.078	231.928	Sn	F
13	692.677	419.527	Zn	F
14	933.473	660.323	Al	F
15	1234.93	961.78	Ag	F
16	1337.33	1064.18	Au	F
17	1357.77	1084.62	Cu	F

(*1)All substances except ^{3}He are of natural isotopic composition;
e-H_2 is hydrogen at the equilibrium concentration of the ortho- and para-molecular

forms.

(*2)V: vapour pressure point;
T: triple point(temperature at which the solid, liquid, and vapour phases are in equilibrium);
G: gas thermometer point;
M ,F: melting point, freezing point
(temperature, at a pressure of 101325 Pa, at which the solid and liquid phases are in equilibrium)

Table 2.2 Types of instrument for interpolation of the ITS-90

Types of instrument for interpolation	Applicable temperature range	Principle
Helium vapor pressure thermometer	0.65 K - 5.0 K	Relation of vapor pressure and temperature of helium-4 and helium-3
Interpolating gas thermometer	3.0 K - 24.5561 K	Relation of pressure and temperature of constant volume of gas when use helium-4 and helium-3 as working fluid
Platinum resistance thermometer	13.8033 K - 1234.93 K	Relation of electrical resistance and temperature of platinum
Radiation thermometer	1234.93 K -	Planck's law of radiation

2.2 Principles of Instruments

There are many types of thermometers. The major ones employ the characteristics of expansion and contraction of substance according to the temperature, employ the valuable of electrical characteristics (electrical resistance) of substance according to temperature, or employ characteristics between temperature and heat radiation energy emitted from surface of substance.

Air temperature continuously fluctuates within a range of 1 to 2 °C over individual periods of several seconds. WMO advises that the best representative value of air temperature is the average taken over a one-minute period, meaning that a number of readings should be made if a thermometer with a very small time constant is used. Rapid fluctuations are smoothed with a thermometer that has a large time constant. However, if the time constant is too large, lags in response to temperature variation will cause errors. The time constant of a thermometer varies inversely with the square root of wind speed, and WMO recommends that the time constant be 30 to 60 seconds for a wind speed of 5 ms^{-1}.

2.2.1 Electric thermometers

Electric thermometer includes electrical resistance thermometer, semiconductor thermometer (thermistor) and thermocouple thermometer. Platinum resistance thermometer is explained as a representative electric thermometer in this section.

Platinum resistance thermometer employs platinum characteristics which changes resistance according to the temperature. It allows us to obtain temperature by measuring electrical resistance. High purity platinum is used since contaminants greatly affect resistance. Sensor for meteorological observation is made with thin sheet of mica or porcelain wrapped with platinum wire, and it is placed in stainless protective tube which has excellent thermal conductivity and corrosion resistant then made it to complete water proof. Diagram of sensor and connection of platinum resistant thermometer is shown in Figure 2.3.

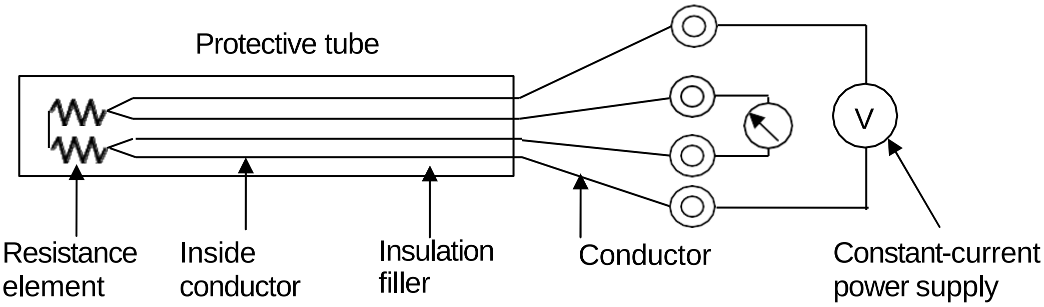


Figure 2.3 Diagram of sensor and connection of platinum resistant thermometer(4 conductor system)

Resistance change of platinum according to temperature is converted to electrical signals (current or voltage signal) by converter. Then the signal is sent to indicator or recorder and displayed or processed as atmospheric temperature. An example of the relation between temperature and resistance of platinum resistance thermometer is shown in Figure 2.4.

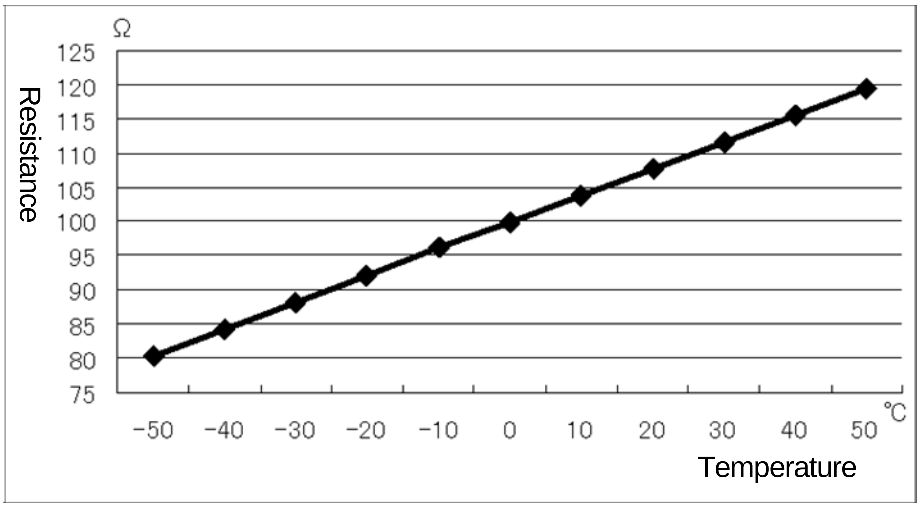


Figure 2.4 Example of the relation between resistance and temperature of platinum resistance thermometer (Source: Japanese Industrial Standard(JIS), Resistance thermometer sensors (JIS C1604))

The advantage of platinum resistance thermometer is the electric measurement which allows remote measurement and automated observation. The disadvantage is necessity of ensuring stable power supply to platinum resistance.

There are 2-conductor system, 3-conductor system and 4-conductor system in the method of inside conductor connection (Figure 2.5). 2-conductor system is impractical because it is unable to remove effect of conductor resistance. 3-conductor system consists of 2 conductors on one terminal of a resistance element and 1 conductor on the other terminal. This method enables to remove effect of conductor resistance. However, this is based on the premises, conductor has identical material, length and electrical resistance and temperature distribution must be the same. 4-conductor system consists of 2 conductors connected on each terminal of resistant element. This method can remove effect of conductor resistant. 4-conductor system has the highest accuracy as a thermometer.

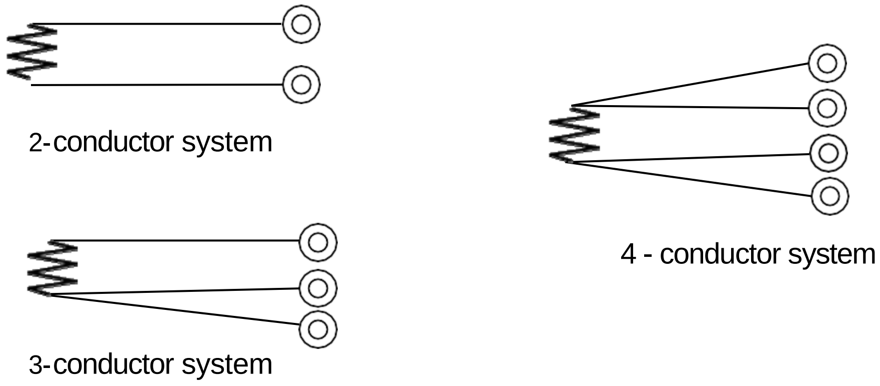


Figure 2.5 Diagram of inside conductor connection

2.2.2 Liquid-in-glass Thermometers

A liquid-in-glass thermometer measures temperature based on the thermal expansion of mercury or spirit alcohol in a glass container. The boiling point of mercury is 356.72 °C, and its melting point is -38.86 °C. The boiling point of methyl alcohol is 64.65 °C, and its melting point is -97.78 °C. Because mercury has low thermal capacity, high heat conductivity, inertness in relation to a glass capillary tube and a high boiling point, it is an ideal thermometric liquid except for its relatively high melting point. Accordingly, mercury thermometers are used for ordinary meteorological observations, and spirit thermometers are used for those involving temperatures below the melting point of mercury.

A liquid-in-glass thermometer consists of a capillary glass tube with a bulb at one end filled with a thermometric liquid, vacuumed and sealed. By reading the position of the liquid level on a scale, a temperature value can be obtained. Designs can be classified as either the sheathed type or the unsheathed type. A sheathed thermometer consists of a bulb, a slender capillary glass tube connected to it, a milky-white scale plate attached to the capillary tube, and an outer glass tube that encloses them. An unsheathed thermometer consists of a thick-walled capillary glass tube with a scale marked directly on it.

The advantages of liquid-in-glass thermometers are their simple design, simple observation method and the possibility of temperature measurement anywhere as they require no electric power for operation. The disadvantage is that careful handling is required because the glass material is fragile.

Several types of liquid-in-glass thermometers are used to measure maximum temperature, minimum temperature and soil temperature in addition to ordinary air temperature.

(1) Maximum thermometers

A maximum thermometer is a mercury thermometer used to measure the maximum temperature within a certain period. It has a narrow part in the capillary tube where mercury passage is constricted between the bulb and the starting point of the scale (Figure 2.6). As the air temperature rises, the mercury exits the bulb and passes through the constriction. When the air temperature falls, the mercury column breaks at this point.

Thus, the mercury in the capillary tube cannot return to the bulb, and remains in the column indicating the maximum temperature.

Observation of maximum temperature is carried out once or twice a day. After measurement, the thermometer is held at the head and the mercury in the capillary tube is shaken back into the bulb to reset its indication to the current air temperature.

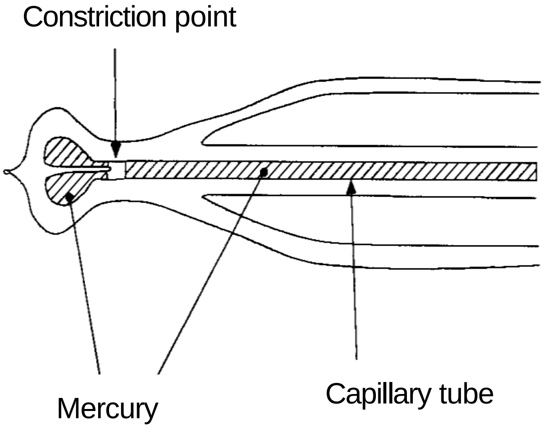


Figure 2.6 Constriction point of a maximum thermometer

(2) Minimum thermometers

A minimum thermometer is a spirit thermometer used to measure the minimum temperature within a certain period. It has a dumbbell-shaped index of colored glass in the spirit column (Figure 2.7). As the air temperature falls, the index is dragged by the surface tension of the spirit and moves toward the bulb with the top of the column. When the temperature rises, the index is left in position because the spirit flows through it. As a result, it remains in the column indicating the minimum temperature.

Observation of minimum temperature is carried out once or twice a day. After measurement, the column is inclined while keeping the bulb higher than the head, and the index is gradually slid back to the top of the column.

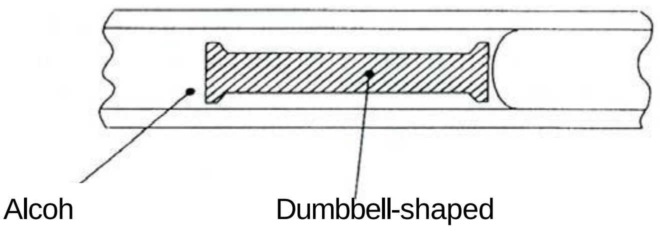


Figure 2. 7 Dumbbell-shaped index of minimum

(3) Soil thermometers

A bent-stem soil thermometer is generally used to measure soil temperature between the ground surface and a depth of 20 cm underground, and has a bend between the bulb and the scale (Figure 2.8). To install this type of thermometer, the bulb should be buried at the prescribed depth with the scale above the ground. The ground surface above the bulb should not be shaded. The scale above the ground should be supported on a post and shielded from solar radiation with a small sunshade made of white painted wood or aluminum. When setting up the thermometer to measure the ground surface temperature, it should be ensured that the bulb is buried close to the ground surface in such a way that exposure is avoided.

When soil is frozen or covered with snow, soil thermometers should be removed to prevent damage.

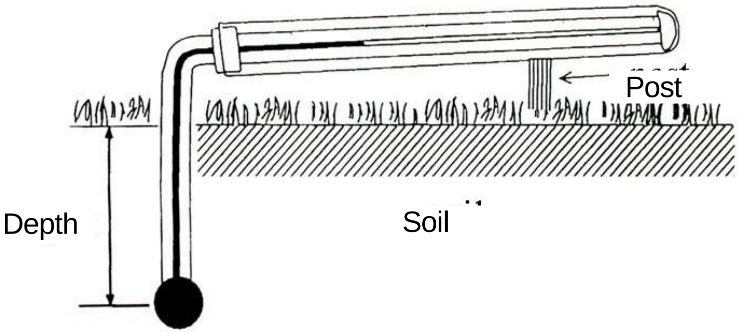


Figure 2. 8 Bent-stem soil thermometer

To measure soil temperatures at greater depths of 50 to 100 cm, a steel pipe of the desired length is driven into the soil and a mercury-in-glass thermometer is suspended in the pipe with a chain. A thermometer with a large time constant should be used to minimize any change in indication between removal from the pipe and reading. With this setup, it takes time for the indication to stabilize once the thermometer is placed underground. In order to minimize changes in indication during measurement and to protect the thermometer, it is advisable to cover the bulb with a rubber cap or install the unit in a wooden, glass or plastic pipe coated with wax or metallic paint.

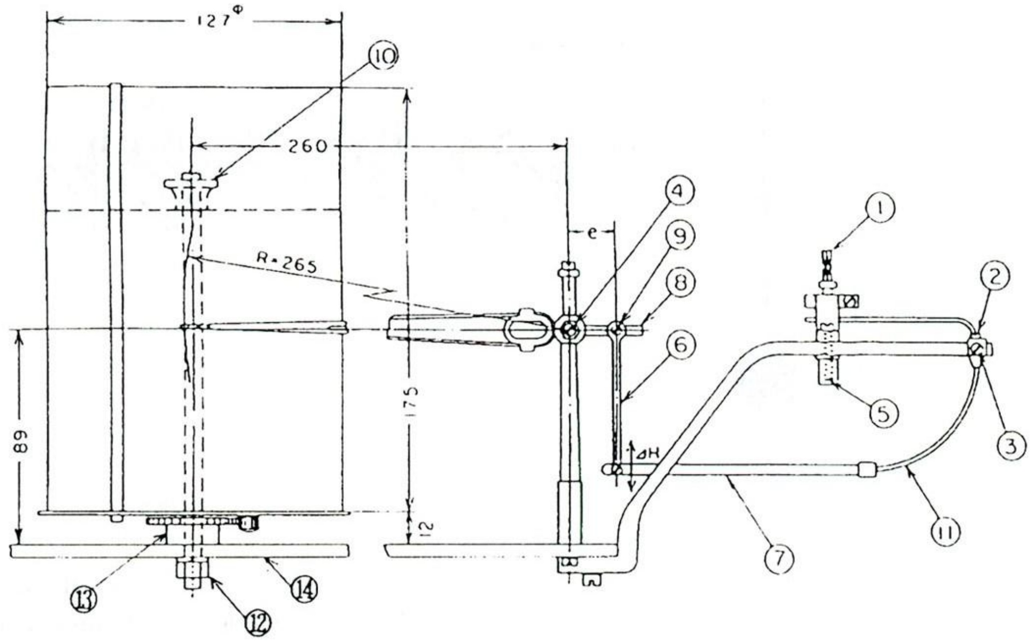
Other types used as soil thermometers are thermographs consisting of a mercury temperature sensor with a recorder connected by a fine metallic tube filled with mercury, platinum resistance thermometers and thermocouple thermometers.

2.2.3 Bimetallic Thermographs

A bimetallic thermograph is a unit consisting of a bimetal and a clock-driven drum on which a recording chart is wound. The curvature of the bimetal changes in response to temperature variations, and this curvature change is recorded on a chart. The bimetal consists of two metal plates with different expansion coefficients welded or brazed and then rolled to an appropriate thickness. As the temperature changes, the bimetal curves due to the difference in the expansion coefficients of the two metals. This change is mechanically magnified and then recorded.

The structure of a bimetallic thermograph is shown in Figure 2.9. When the bimetal ⑪ curves in response to temperature change, the bimetal lever ⑦ attached to the end of the bimetal moves with it. This motion is transmitted to the magnification adjustment lever ⑧ via the steel strip ⑥, and moves the pen arm attached to the magnification adjustment lever. In this way, the temperature change causing the bimetal to curve is recorded on the chart on the clock-driven drum with the pen tip at the end of the pen arm.

The advantage of bimetallic thermographs is that air temperature can be charted over a certain period even where no electric power supply is available. The disadvantages are that its accuracy is lower than those of liquid-in-glass and electrical thermometers, its mechanism does not allow continuous recording over long periods, and remote sensing is not possible.



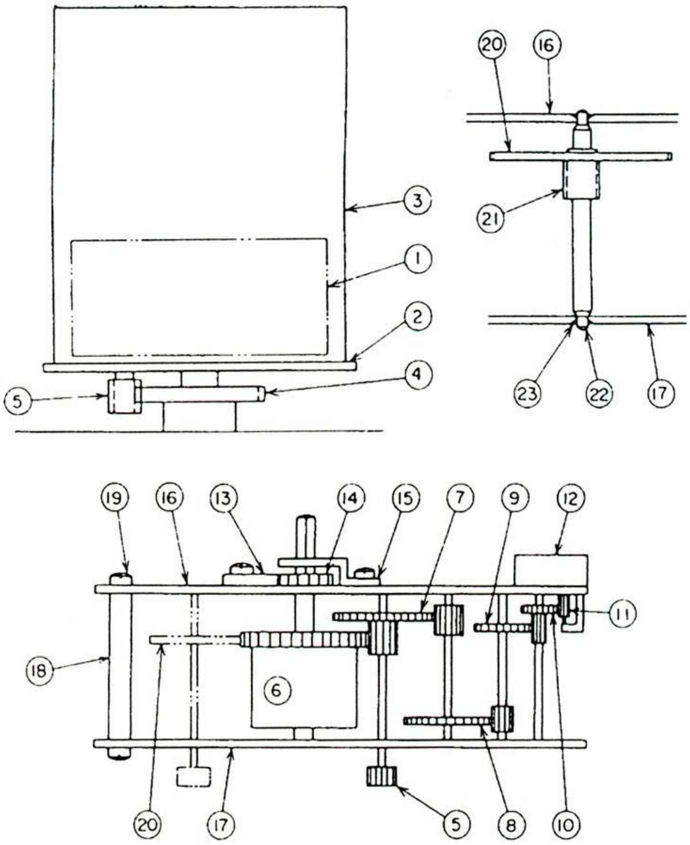
① Indicator adjustment screw ② Sensor attachment screw ③Stopping screw
④ Nut to stop pen arm ⑤ Spring ⑥ Steel strip
⑦ Bimetal lever ⑧ Magnification adjustment ⑨ Screw to stop
⑩ Screw pushing clock-driven drum ⑪ Bimetal ⑫ Attachment nut for clock-driven drum axis
⑬ Washer ⑭ Stand table Unit: mm

Figure 2. 9 Bimetal thermograph structure

2.2.4 Clock-driven Drums

A clock-driven drum is a self-registering instrument that rotates at a constant rate and creates a record on a chart around it. It runs on a spring-driven or battery-powered clock, and the typical recording period is one or seven days.

The structure of a one-day spring-driven drum is shown in Figure 2.10. The clockwork is held in the clock-driven drum *A*. The force of the spring wound up in the spring box ⑥ is transmitted through the gears to the rotation-driving unit ⑫, which causes the clock drum to turn at a constant rate. The drum can be turned by hand as needed to synchronize the time lines on the recording chart. A seven-day drum has an additional gear ⑳ meshed with the gear in the spring box, and a rotation adjustment gear ⑤ is attached to the shaft of the additional gear to reduce the speed of the drum.



① Clock device
② Bottom plate
③ Cylinder of clock-driven drum
④ Central gear
⑤ Rotation adjustment gear
⑥ Spring box
⑦ Second gear
⑧ Third gear
⑨ Fourth gear
⑩ Fifth gear
⑪ Interaction pinion
⑫ Rotation-driving unit
⑬ Unit pushing gear connecting to spring box
⑮ Attachment to gear connecting to spring box
⑯ Upper panel
⑰ Lower panel
⑱ Stay
⑲ Screw attaching to stay
⑳ Gear
㉑ Pinion
㉒ Pivot
㉓ Oil reservoir

Figure 2. 10 Names of clock-driven parts

2.2.5 Louvered Screens

Louvered screens (Figure 2.11) protect thermometers and psychrometers from rain and wind as well as solar and other types of radiation. Ideally there should be a double louver at the sides and a double drain board at the bottom, and the roof should consist of two layered boards that allow airflow between them. There is usually a single door, but some screens in low-latitude areas have two doors to the north and south. Screens must be placed so that the thermometers inside are not exposed to direct sunlight when the door is opened, and should be designed with a small heat capacity while allowing adequate space between the walls and the instruments. Both the inner and outer sides of screens should be painted white and be water repellent. Most are made of wood, but some are made of plastic.

Because of solar and other types of radiation, the temperature of a screen may be higher than the air temperature if the level of radiation is intense, and conversely may be lower than the air temperature on a clear night. As a screen has high heat capacity, its temperature change lags behind variations in air temperature – a tendency that is remarkable when the wind is weak. To measure air temperature accurately, it is necessary to ventilate the thermometer in order to keep it and the outer air as close to thermal equilibrium as possible. Since temperatures measured with thermographs and maximum or minimum thermometers without ventilation are subject to the influence of screen temperature, their values tend to be higher by day and lower by night than values measured with a ventilated thermometer.

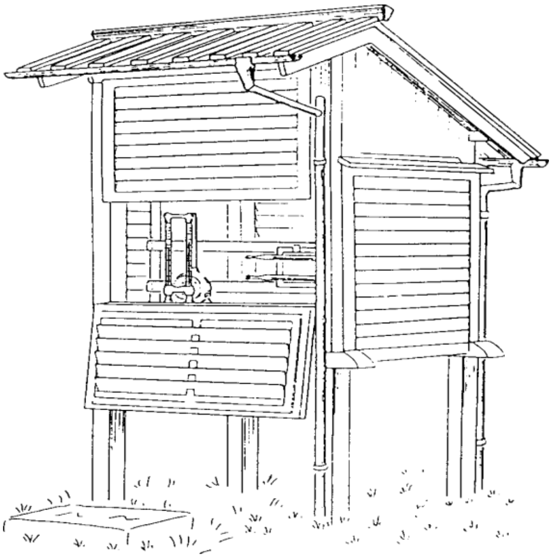


Figure 2.11 Louvered screens

2.2.6 Ventilated Shields

Ventilated shields are used to protect the sensors of instruments such as platinum resistance thermometers from solar and heat radiation. Forced ventilated shields (Figure 2.12) consist of a double cylinder made from corrosion-resistant material. A heat insulator between the inner and outer cylinders isolates heat, and the lustrous surface precludes the influence of solar and other types of radiation. An electric fan at the top provides ventilation to keep the sensor and the outer air in thermal equilibrium.

WMO recommends a ventilation speed of 2.5 to 10 m/s. JMA sets ventilators to provide an air speed of 5 to 7 m/s.

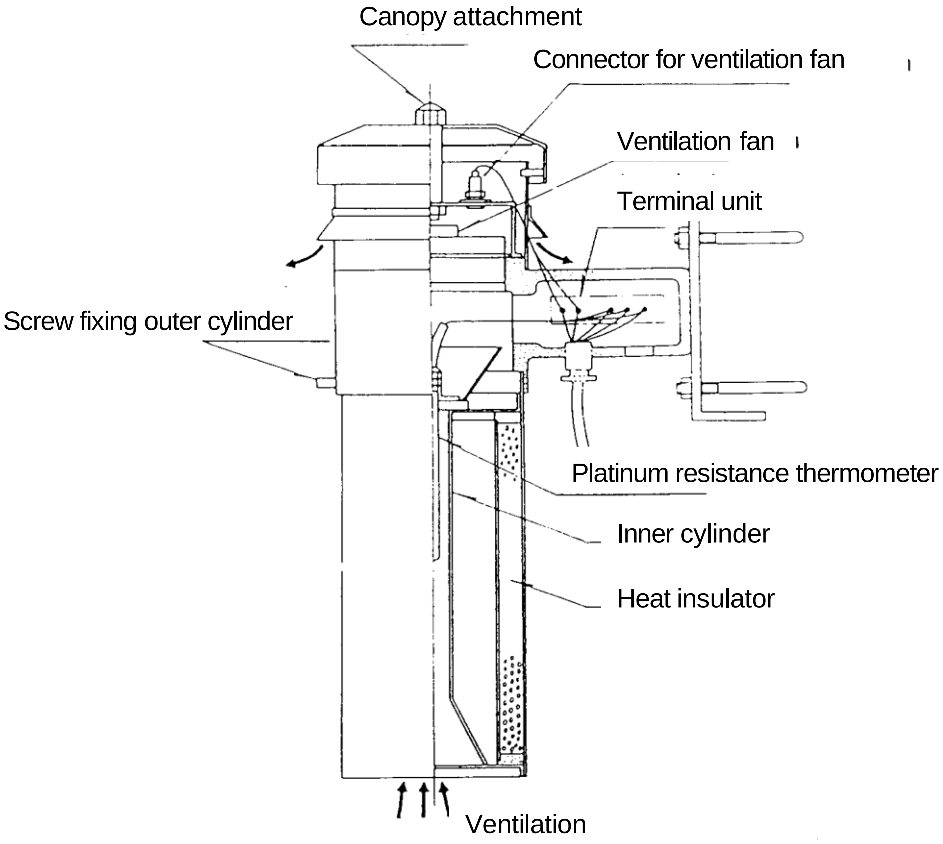


Figure 2. 12 Ventilation type thermometer shelter

2.3 Exposure and Siting

Thermometer installation should be standardized to ensure measurements that represent the ambient atmosphere and are comparable with those obtained at different places and at different times.

2.3.1 Observation Fields

An observation field is an area in which instruments are arranged in an efficient and appropriately concentrated manner. It should be level, open, flat and unshaded by trees or buildings. The ground surface should be covered with grass or maintain its natural surface on barren land, and the field should be enclosed with a fence that does not disturb wind passage. The ground should be kept clear all year round by mowing and weeding the surface occasionally. Locations on steep slopes or in hollows should be avoided because of the poor representation that results from such terrain. Any influence from changes in the surrounding conditions of the field must be taken into account. A power source and water supply for management and maintenance of the observation field and instruments are beneficial.

2.3.2 Louvered Screens and Ventilated Shields

Louvered screens or ventilated shields should be placed in observation fields as described in the previous section.

The foundations of louvered screens should be made of a sturdy material and installed firmly to reduce errors in the readings of maximum and minimum thermometers resulting from wind vibration.

Ventilated shields should be installed vertically. If an electric fan is used for ventilation, heat from the motor or the fan should not affect the thermometer.

2.3.3 Thermometers

Due to the influence of radiation, the temperature gradient near the ground is larger at lower elevations. Accordingly, a thermometer placed close to the ground will tend to indicate higher temperatures during the daytime and lower values at night, and it is therefore recommended that general observations of air temperature be made at a height of 1.25 to 2 m above the ground (JMA sets thermometers at a height of 1.5 m). Temperature observation on the tops of buildings is not recommended because of the variable vertical temperature gradient present and the effect of radiation from the building itself.

Liquid-in-glass thermometers, including ordinary thermometers, maximum and minimum thermometers and bimetallic thermographs, are installed in louvered screens. Maximum thermometers should be installed in a position inclined about 2 degrees from the level with the bulb lower so that gravity acting on the column does not exert a force on the constriction. On the other hand, minimum thermometers should be installed level. Electrical thermometers may be installed in ventilated shields or in louvered screens.

2.4 Maintenance

2.4.1 Routine Maintenance

2.4.1.1 Electrical Thermometers

Defective contacts may cause jumps in the air temperature record. Check for such jumps and perform repair if necessary.

2.4.1.2 Liquid-in-glass Thermometers

(1) As dust or salt accumulation on the glass prevents clear readings, wipe occasionally with a cloth.

(2) If bubbles or breakage in the liquid column are found, repair is necessary.

(3) If mercury adheres to the inner wall of the capillary tube and reading the scale becomes difficult, replace the thermometer as such defects cannot be repaired.

(4) If the indication of a maximum thermometer in the vertical is different from that in a horizontal position by 0.2 °C or more, the unit should be replaced. This phenomenon is often seen when breakage in the mercury column occurs.

(5) A minimum thermometer whose index does not move with the top of the column and is left outside it cannot be repaired; replacement is necessary.

(6) If dew forms on the inner wall of the outer tube of a sheathed thermometer and reading the scale becomes difficult, replacement is necessary as the outer tube may be cracked.

2.4.1.3 Bimetallic Thermographs

(1) The reading of a bimetallic thermograph should be compared with the temperature of an aspirated psychrometer for each observation. If the difference between them exceeds 1 °C, adjust the bimetallic thermograph indicator.

(2) Dust, salt and exhaust gases are likely to accumulate on a thermograph when it is used in a louvered screen. Wipe exposed parts, pivots, bearings and the bimetallic element with a brush from time to time.

(3) If the pen moves irregularly, repair is necessary.

2.4.1.4 Clock-driven Drums

Regularly check the accuracy of the clock. If it is found to be inaccurate, detach the clock-driven drum and use the pace adjustment lever.

2.4.1.5 Louvered Screens

Always keep the inside of louvered screens clean. After a snowstorm, for example, remove any buildup of snow from them.

2.4.1.6 Ventilated Shields

Check that the fan is operating. If any unusual noise or vibration is found, detach and inspect.

2.4.2 Periodic Maintenance

2.4.2.1 Electrical Thermometers

(1) Electrical thermometers should be checked at least every three months using a portable aspirated psychrometer. Comparisons should be avoided in bad weather conditions such as those with strong wind, heavy rain/snow or dense fog, and a time when the air temperature is relatively stable should be chosen. When installing a portable aspirated psychrometer, ensure that its intake is at the same level as that of the electrical thermometer.

(2) Electrical thermometer observation errors can result from even small changes in contact resistance or slight deteriorations of insulation caused by dust or salt deposits. Ensure that wire connection terminals are tightened, and clean them with alcohol once a year.

2.4.2.2 Liquid-in-glass Thermometers

The spirit in spirit thermometers sometimes evaporates, adheres or condenses in the upper part of the capillary tube, producing errors in reading. To prevent such problems, immerse the bulb in cold water or ice and blow steam over the upper part of the tube at regular intervals to move adhered spirit back to the bulb.

2.4.2.3 Bimetallic Thermographs

Periodic maintenance of thermographs should be carried out every three months.

(1) Perform routine maintenance meticulously.

(2) If ink has solidified and soiled the pen tip, pull the tip from the pen arm and immerse it in alcohol to rinse it. If the ink passage is clogged and the pen has poor ink flow, clean its tip by inserting a firm but thin piece of paper into the split.

(3) If the traced line has become bold, replace the pen.

(4) Clean the bimetal using a brush soaked with benzine. After it has dried, wipe it with a lightly greased cloth to prevent corrosion. Do not apply too much grease, as a thick layer may affect sensitivity.

(5) Turn the indicator adjustment screw ① shown in Figure 2.9 to check whether the movement of the pen tip aligns with the time lines over the entire range. If misalignment occurs, adjust the curvature.

2.4.2.4 Clock-driven Drums

Clock-driven drums may stop due to oil shortage or deterioration. It is necessary to clean and oil the drum every two or three years. If installed in a louvered screen, a clock may stop within two years from the influences of briny air, volcanic gases, automobile exhaust gases and agricultural pesticides. When such conditions are present, more frequent inspection is required.

2.4.2.5 Louvered Screens

Wash louvered screens once or twice a year to remove soiling. If paint has peeled or soiling is difficult to remove, repaint the screen. Repainting is necessary at least once a year in areas with significant air pollution.

2.4.2.6 Ventilated Shields

Ventilated shields should be dismantled and cleaned at regular intervals to ensure efficient ventilation around the thermometer.

2.5 Calibration

All liquid-in-glass thermometers undergo a gradual shift of their zero point. It is important to inspect them at regular intervals - usually every five years. Electrical thermometers should also be inspected in a similar manner in order to monitor drift.

JMA calibrates thermometers at its calibration center using the methods described below for use at observatories.

2.5.1 Freezing-point Calibration

The temperature of 0°C is defined as that at which ice is in equilibrium with air-saturated water under standard pressure conditions. Accordingly, ice is generally used for freezing-point calibration. Care must be taken, as a temperature of 0 °C is not attained if the ice contains impurities, especially salt. Freezing-point testers (Figure 2.12), which have a hole at the bottom to allow water to drain and a thermometer, should be cleaned prior to inspection. Crush the ice to an appropriate size and place it in the freezing-point tester. Then, insert the thermometer into the tester (insert vertically for liquid-in-glass thermometers) and pack it with the crushed ice so that the entire unit is buried. When packing with crushed ice, be sure to fill the tester so that the ice comes into close contact with the bulb.

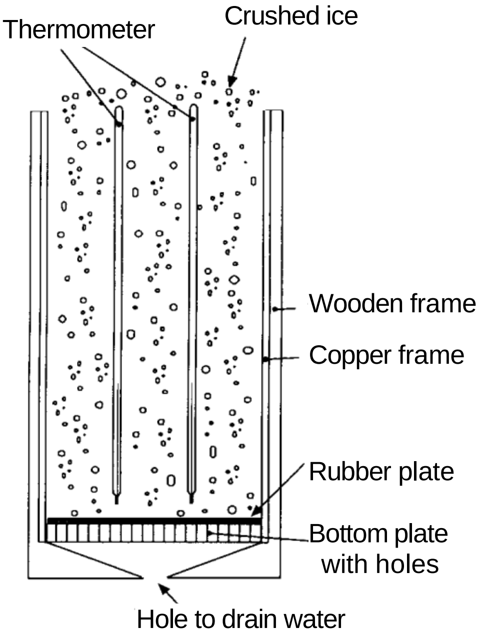


Figure 2.12 Freezing-point tester

2.5.1.1 Electrical Thermometers

Freezing-point calibration of platinum resistance thermometers (the four-wire type) is described in this section. A diagram of the circuit used for calibration is shown in Figure 2.13

(1) Wash the freezing-point tester and the platinum resistance thermometer well before calibration. Turn on the digital voltmeter and voltage current generator and wait for at least 30 minutes to allow them to stabilize.

(2) Crush ice finely in the same manner as for liquid-in-glass thermometer calibration. Insert the platinum resistance thermometer into the freezing-point tester, connect the wires as shown in Figure 2.13 and ensure close contact with the ice.

(3) Adjust the zero point of the digital voltmeter by turning S2 in Figure 2.13 to the short-circuit side and by turning the zero shift knob of the digital voltmeter.

(4) Turn the knife switches S1 and S2 to the standard resistance measurement side. A current close to the prescribed value will flow through the circuit.

(5) Keep the current at the prescribed value by turning the adjustment knob of the reference voltage current generator while watching the terminal voltage *ES* across the standard resistor *RS* with the digital voltmeter.

(6) At about 30 minutes after starting to keep the prescribed current, check the contact between the platinum resistance thermometer and the ice and begin the reading. Check the null point of the digital voltmeter first. Read the *ES* value and the voltage between the terminals of the platinum resistance thermometer *ER* alternatively two or more times. If the resulting readings indicate the same value, use that value. If two or more resistors are wired as shown in Figure 2.9, change the connections of terminals A and B successively.

(7) Calculate the resistance of the thermometer using the value derived in Step (6).

Assuming that RT is the resistance to be obtained, that RS is the resistance of the standard resistor, and that I is the measuring current, Ohm's Law provides the following equations:

$$ER = RT \cdot I \quad \text{and} \quad ES = RS \cdot I$$

and the resistance value of the sensor RT at 0°C is derived from the following equation:

$$RT = RS \cdot ER/ES$$

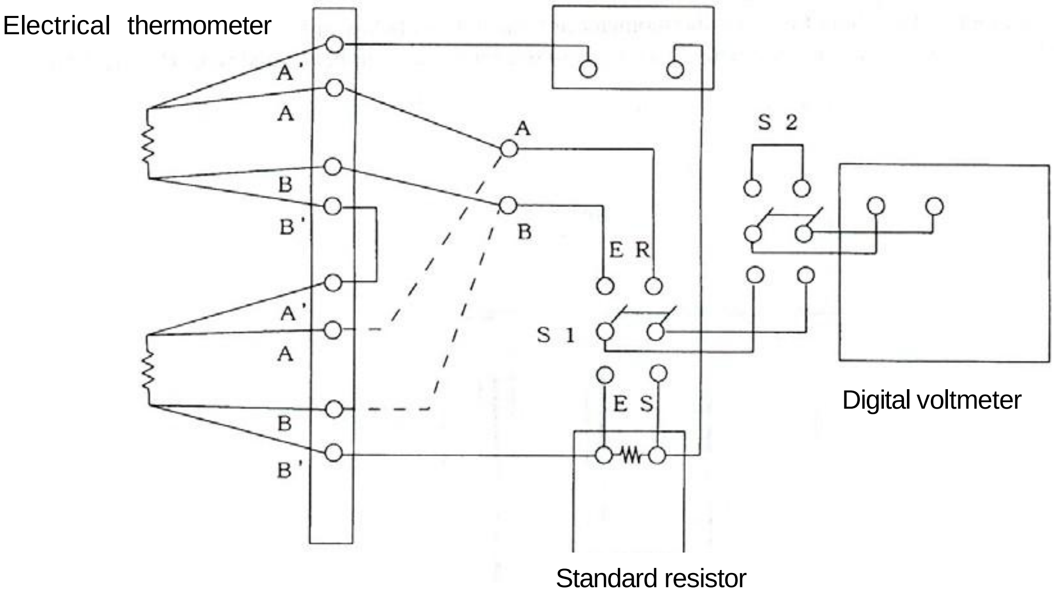


Figure 2.13 Diagram of an electrical thermometer calibration

2.5.1.2 Liquid-in-glass Thermometers

If the thermometer is too long to be covered completely, bury it at least up to the 20 °C mark. However, do not insert it so deeply that the bulb reaches the bottom of the tester.

When using ice with a temperature of lower than 0 °C, pour some pure water on it to bring its temperature up to 0 °C.

Unsheathed mercury thermometers can be inserted directly into the ice. However, because sheathed units have some amount of heat capacity, they should be cooled prior to insertion. Do not insert spirit thermometers into ice quickly; if a unit indicating a temperature of above 0 °C is inserted quickly, the spirit column may adhere to the wall of the capillary tube and the reading at freezing point may become lower by 0.1 to 0.2 °C.

Leave the thermometer in the ice for more than 10 minutes before reading the indication, and push aside ice so that the 0°C mark is visible without moving the thermometer. Leave the thermometer in the ice and add a small amount of crushed ice after the first reading. After several minutes, take another reading. If the first and second indications are the same, that value is determined as the instrument error at 0 °C. If the two indications are different, the thermometer may not be in equilibrium with the ice at freezing point, and the freezing point should be calibrated again.

Voids develop as ice melts and its amount decreases, especially near the bulb. It is therefore important to squeeze the ice before reading to ensure that the thermometer and ice are in close contact. Freezing-point calibration of a maximum thermometer is carried out by leaving it in a freezing-point tester for more than 10 minutes. After this period of time, pull the thermometer out a little, tap it lightly on the rubber plate under the ice a few times and take a reading. Repeat these operations until the indication has settled, and derive the instrument error from the indication. Even when the thermometer is tapped on the rubber plate, ensure that the bulb is kept in the ice.

2.5.2 Calibration other than Freezing Point

2.5.2.1 Electrical Thermometers

Calibration of thermometers is carried out using a reference thermometer in a temperature calibration chamber by comparing both measurement values of a reference thermometer and tested thermometers (Figure 2.14).

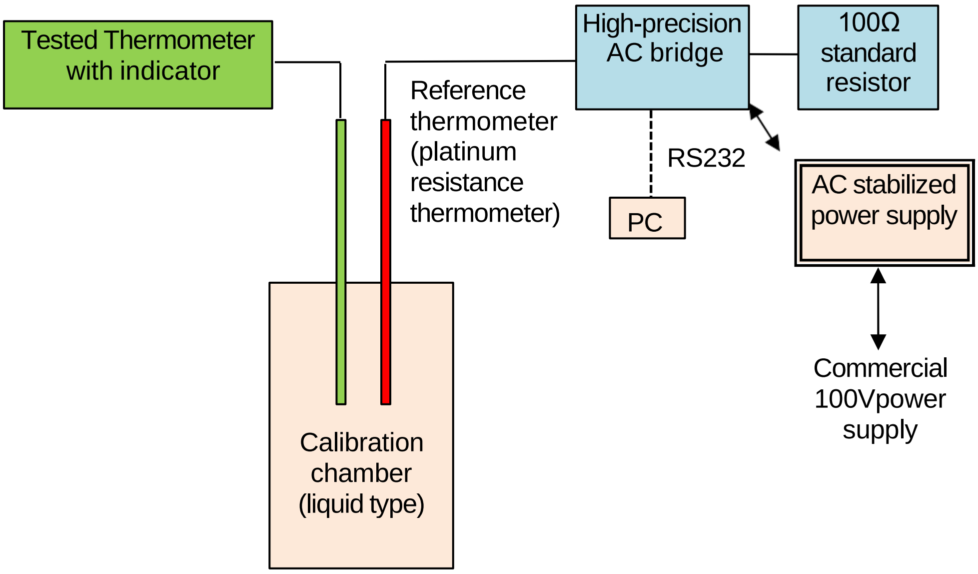


Figure 2.14 Comparative calibration of an electrical thermometer (An example in JMA)

2.5.2.2 Liquid-in-glass Thermometers

Calibration of liquid-in-glass thermometers at temperatures other than freezing point is carried out using a reference thermometer in a temperature calibration chamber (liquid type) (Figure 2.15).

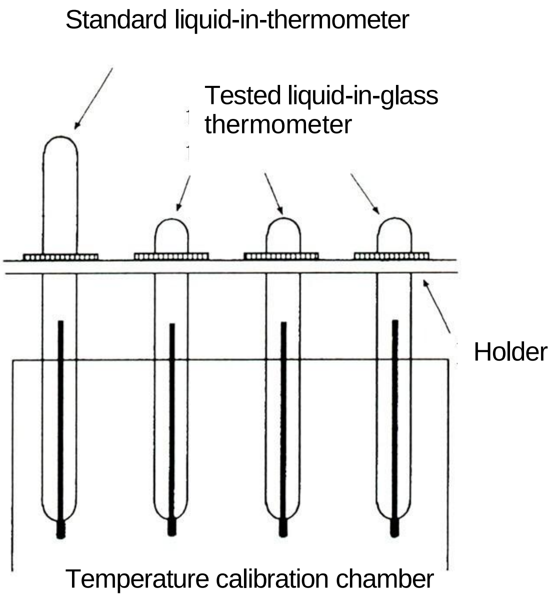


Figure 2.15 Comparative calibration of a liquid-in-thermometer (An example in JMA)

2.5.2.3 Bimetallic Thermographs

Bimetallic thermographs are calibrated in a temperature calibration chamber (air type) with its protective frame removed. Calibration is performed at three or four temperatures across the unit's entire measurement range using a reference thermometer.

2.6 Adjustment and Repair

2.6.1 Electrical Thermometers

If there is a large difference between the actual temperature and the reading of an electrical thermometer, detach the cables of the sensor (i.e., the platinum resistance thermometer) from the terminals and connect a standard resistor (of equivalent temperature) to the terminals in its place to determine whether the fault is in the sensor or in the electrical circuit. If the sensor is at fault, replace it. If the electrical circuit is at fault, it is impossible to repair it on the spot. Consult a technical expert or the manufacturer for repair. As improper tightening or defective insulation of terminals can cause faults, inspect the cables extending from the sensor to the electrical circuit and try retightening the terminals.

2.6.2 Liquid-in-glass Thermometers

2.6.2.1 Basic Instructions

(1) Because glass is fragile, repeated repairs are often required. Choose an appropriate method and repeat repair carefully as many times as needed.

(2) When a thermometer is repaired, refrain from using it for a few days until its indication stabilizes. Set spirit-in-glass thermometers vertically during the stabilization period.

2.6.2.2 Visible Issues

(1) If graduation lines on an unsheathed thermometer become blurred, they can be clarified by applying black enamel or lacquer and wiping off with a piece of hard paper.

(2) If the cap of a sheathed thermometer comes off, attach it again with an adhesive.

(3) If there is any looseness between a thermometer and the board to which it is attached, insert a piece of rubber between the unfastened clasps and the thermometer and fasten the clasps again.

(4) The scale plate of a sheathed thermometer is installed in the outer glass tube. If it comes loose, the thermometer cannot be repaired; the same applies for cracking and other damage in the glass portion.

2.6.2.3 Breakage in the Mercury Column

Breakage in the mercury column occurs when a bubble remains in it. This is often seen when mercury thermometers are transported or stored carelessly. Thermometers that are always oriented vertically can be used without problems if the bubble is small enough to be invisible without a magnifying glass. However, a bubble left as it is may become larger and make repair difficult. Repair should be performed while the bubble is small.

If the problem cannot be remedied using one method, try others as necessary.

(1) Repair by tapping

Try tapping the bulb of the thermometer on a rubber plate. If the bubble moves toward the top of the mercury column, continue tapping. Tap in the direction of the thermometer’s axis; do not tap in a transverse or oblique direction, as this will cause the glass to break. If the bubble does not move, or if it moves toward the bulb, try another method.

(2) Repair by centrifugal force

Grip the thermometer at the head tightly and shake it forcefully. The mercury in the capillary tube will be forced toward the bulb by centrifugal force, and as a result the bubble will be expelled to the top of the mercury column.

(3) Repair by temperature difference

Cool alcohol with dry ice to a temperature below the scale range of the thermometer. Immerse the bulb of the thermometer in the alcohol so that all the mercury flows into the bulb, and the bubble will be eliminated.

If a thermometer has a safety chamber at the top of the capillary tube, warm the bulb in lukewarm water. When the bubble reaches the safety chamber and the lower mercury unites with the upper mercury, cool the bulb slowly and the bubble will disappear. Remember that too much warming may cause the mercury to burst through the top of the capillary tube.

2.6.2.4 Breakage in the Spirit Column

Perform repair as outlined in (2) and (3) of Section 2.6.1.3.

2.6.3 Bimetallic Thermographs (see Figure 2.9.)

2.6.3.1 Adjustment of Indication

(1) Large shifts in indication

When the indication position needs to be shifted significantly for seasonal changes, turn the indicator adjustment screw ① near the temperature sensor.

(2) Small shifts in indication

To shift the indication position slightly for small corrections of instrument error, turn the pen arm adjustment screw near the pen arm rotation axis.

When the indication position is shifted, tap the instrument body, observe the movement of the pen and make sure its position is stable. To adjust the indication, place the bulb of a reliable liquid-in-glass thermometer close to the bimetallic strip of the thermograph when the temperature is practically constant. Leave them for several minutes and then make the adjustment. Leave them for several minutes again and check that both indicate the same temperature.

(3) Unstable indication

Inspect for looseness of the indicator adjustment screw ①, the sensor attachment screw ②, the set-screw ③, the pen arm attachment nut ④, the pen arm spring ⑤, the pen arm attachment screw, the pen arm-supporting pivot, and the attachment of the pen tip. Tighten any loose parts. Adjust the pivots at both ends of the pen arm rotation axis so that the bottom of the steel strip ⑥ touches the bimetal lever ⑦ lightly when the top of the link is held and allowed to hang down.

2.6.3.2 Irregular Movement of the Pen

Irregular movement of the pen during its up and down motion may occur if excessive friction is exerted between the pen tip and the recording chart or if rotating parts are faulty. Typical causes of such irregular movement are as follows:

(1) Defective pen tip

Irregular movement often occurs when a pen tip is replaced. Polish the tip a little on an oilstone. If a pen tip is damaged, replace it.

(2) Improper pen pressure

If the instrument has a pen pressure adjustment screw, change the pressure so that the tip separates from the recording chart when the instrument body is inclined by about 30 degrees to the front. Repeat this adjustment with the pen tip position in the upper and lower parts of the recording chart.

If irregular movement of the pen occurs in particular parts of the recording chart, the shaft of the clock-driven drum may be inclined or the distance between the drum shaft and the pen arm rotation axis may not be correct.

- Inclined clock-driven drum shaft

  Bring the drum shaft to the correct position by loosening the fixing nut ⑫ and the rotating washer ⑬, or by inserting a piece of paper between the washer ⑬ and the lower plate ⑭.

- Improper pen arm length

  Measure the distance from the pen arm rotation axis (the center of the nut ④) to the pen tip, and move the tip to the correct position.

(3) Loosened screws in various parts

It is difficult to specify the play of various parts and the tightening of screws quantitatively. An instrument that operates well should be examined to get a feel of the situation.

(4) Soiled pivot rotation parts

If dust accumulates on pivot rotation parts, friction develops and the movement becomes dull. Clean pivots from time to time. If rust develops on them, clean them and oil lightly. When cleaning pivots, always clean one pivot rotation part at one end, reassemble and adjust the play before cleaning the other part on the opposite side. Otherwise, operation may deteriorate further.

2.6.4 Clock-driven Drums

(1) Clock stoppage

If a clock-driven drum comes to a standstill due to oil shortage or deterioration, dismantle and clean it. As the rotation-driving part contains minute components and performs precision operation, consult a technical expert or the manufacturer for repair.

(2) Clock inaccuracy

Detach the drum and adjust the clockwork using the pace adjustment lever.

2.7 Transport

Transport liquid-in-glass thermometers with the bulb in a low position to prevent breakage of the liquid column. Mercury is widely used for liquid-in-glass thermometers, but is toxic if swallowed or inhaled in vapor form. The International Air Transport Association (IATA) restricts the transportation of mercury by aircraft. Seek advice from the appropriate institution or common carriers.

Chapter 3: Measurement of Sunshine Duration and Solar Radiation

CONTENTS

Chapter 3: Measurement of Sunshine Duration and Solar Radiation

7.1 Measurement of Sunshine Duration

7.1.1 Definition

Sunshine duration is the length of time that the ground surface is irradiated by direct solar radiation (i.e., sunlight reaching the earth's surface directly from the sun). In 2003, WMO defined sunshine duration as the period during which direct solar irradiance exceeds a threshold value of 120 watts per square meter (W/m^2). This value is equivalent to the level of solar irradiance shortly after sunrise or shortly before sunset in cloud-free conditions. It was determined by comparing the sunshine duration recorded using a Campbell-Stokes sunshine recorder with the actual direct solar irradiance.

7.1.2 Sunshine Duration Measuring Instruments

Campbell-Stokes sunshine recorders and Jordan sunshine recorders have long been used as instruments to measure sunshine duration, and are advantageous in that they have no moving parts and require no electric power. Their disadvantages are that the characteristics of the recording paper or photosensitized paper used in them affect measurement accuracy, differences between observers may arise in determining the occurrence of sunshine, and the recording paper must be replaced after sunset.

As sunshine is defined quantitatively at present, a variety of photoelectric sunshine recorders have been developed and are used in place of these instruments. As the threshold value for the occurrence of sunshine is defined in terms of direct solar irradiance, it is also possible to observe sunshine duration with a pyrheliometer.

7.1.2.1 Campbell-Stokes Sunshine Recorders

(1) Principles and Structure

A Campbell-Stokes sunshine recorder concentrates sunlight through a glass sphere onto a recording card placed at its focal point. The length of the burn trace left on the card represents the sunshine duration.

The device’s structure is shown in Figure 7.1 (a). A homogeneous transparent glass sphere L is supported on an arc XY, and is focused so that an image of the sun is formed on recording paper placed in a metal bowl FF' attached to the arc. The glass sphere is concentric to this bowl, which has three partially overlapping grooves into which recording cards for use in the summer, winter or spring and autumn are set (Figure 7.1 (b)). Three different recording cards (Figure 7.1 (c)) are used depending on the season. The focus shifts as the sun moves, and a burn trace is left on the recording card at the focal point. A burn trace at a particular point indicates the presence of sunshine at that time, and the recording card is scaled with hour marks so that the exact time of sunshine occurrence can be ascertained. Measuring the overall length of burn traces reveals the sunshine duration for that day. For exact measurement, the sunshine recorder must be accurately adjusted for planar leveling, meridional direction and latitude. Campbell-Stokes and Jordan sunshine recorders mark the occurrence of sunshine on recording paper at a position corresponding to the azimuth of the sun at the site, and the time of sunshine occurrence is expressed in local apparent time.

Exchange and reading of the recording paper are performed after sunset.

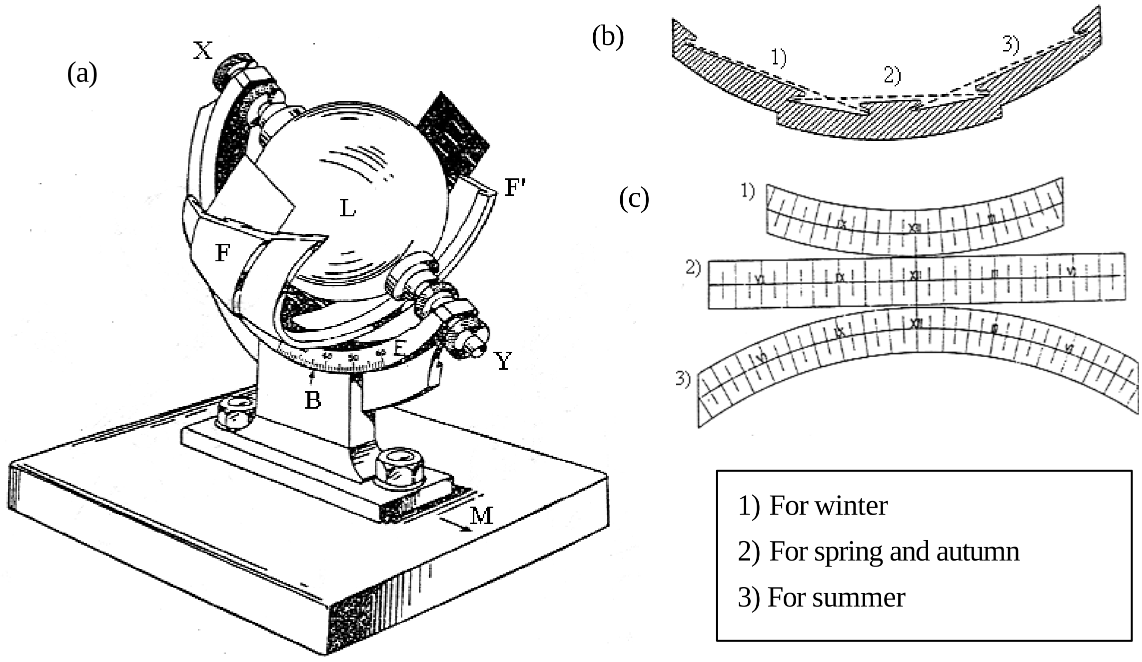


Figure 7.1 Campbell-Stokes sunshine recorder

(a) Structure

(b) Cross section of bowl and grooves

(c) Recording cards

(2) Reading of Recording Paper

To obtain uniform results for observation of sunshine duration with a Campbell-Stokes sunshine recorder, the following points should be noted when reading records:

(a) If the burn trace is distinct and rounded at the ends, subtract half of the curvature radius of the trace’s ends from the trace length at both ends. Usually, this is equivalent to subtracting 0.1 hours from the length of each burn trace.

(b) If the burn trace has a circular form, take the radius as its length. If there are multiple circular burns, count two or three as a sunshine duration of 0.1 hours, and four, five or six as 0.2 hours. Count sunshine duration this way in increments of 0.1 hours.

(c) If the burn trace is narrow, or if the recording card is only slightly discolored, measure its entire length.

(d) If a distinct burn trace diminishes in width by a third or more, subtract 0.1 hours from the entire length for each place of diminishing width. However, the subtraction should not exceed half the total length of the burn trace.

7.1.2.2 Jordan Sunshine Recorders

A Jordan sunshine recorder lets in sunlight through a small hole in a cylinder or a semicylinder onto photosensitized paper set inside the cylinder on which traces are recorded. One common type has two hollow semicylinders arranged back to back with their flat surfaces facing east and west (Figure 7.2 (a)). Each flat surface has a small hole in it. The Jordan sunshine recorder used by JMA is the same in principle, but consists of a hollow cylinder with two holes as shown in Figure 7.2 (b). The instrument has its cylinders inclined to the relevant latitude and their axes set in the meridional direction. Photosensitized paper with a time scale printed on it is set in the cylinders in close contact with the inner surface. When direct solar radiation enters through the hole, the paper records the movement of the sun as a line. Sunshine duration is ascertained by measuring the length of time the paper was exposed to sunlight.

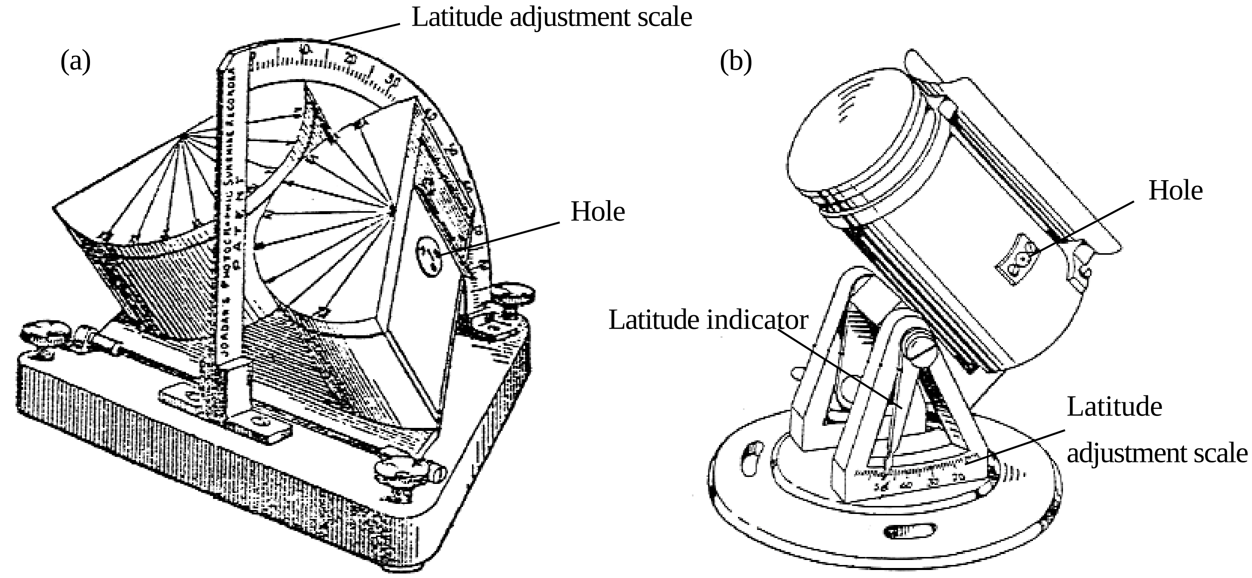


Figure 7.2 Jordan sunshine recorders

(a) Common type

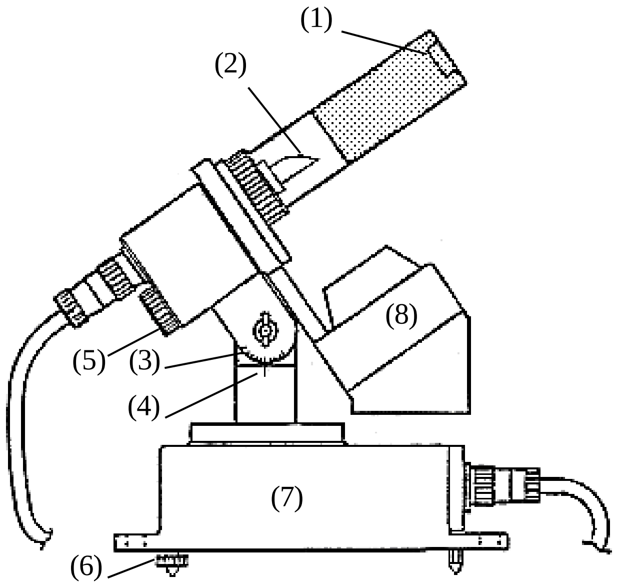
(b) JMA type

7.1.2.3 Other Sunshine Recorders

Since the threshold value for the definition of sunshine is set as a direct solar irradiance of 120 W/m^2, sunshine recorders using photosensors as radiation detectors have been developed. By way of example, rotating mirror and solar-cell-type sunshine recorders are described below.

(1) Rotating mirror sunshine recorder (Figure 7.3)

A rotating mirror sunshine recorder is an application of the scanning method presented in the CIMO Guide. A rotating mirror is used to reflect sunlight onto the photosensor, and the occurrence of sunshine is detected by measuring the intensity of the light received. The rotating mirror sunshine recorder used by JMA has a mirror that rotates once every 30 seconds and a photosensor to receive the reflected sunlight. Once the instrument is set to an angle corresponding to the latitude at the site by adjusting the scale on the body at installation, the double-surfaced mirror reflects sunlight as required throughout the year regardless of changes in the sun’s elevation. Although the radiation received by the photosensor contains both direct solar radiation and diffuse sky radiation, the latter is removed by differentiating the output signal for time electrically, and only direct solar radiation can be detected at the peak of the maximum differential coefficient. The instrument emits a pulse when the signal exceeds the threshold value of 120 W/m^2 corresponding to the definition of direct solar irradiance, and the processing unit counts two minutes of sunshine for every four pulses.



(1) Photosensor
(2) Rotating reflective mirror
(3) Latitude adjusting scale
(4) Latitude adjusting mark
(5) Desiccant container
(6) Level adjusting screw
(7) Converter
(8) Fan

Figure 7.3 Rotating mirror sunshine recorder

(2) Solar-cell-type sunshine recorder (Figure 7.4)

A solar-cell-type sunshine recorder is an application of the contrast method presented in the CIMO Guide. It uses solar cells and determines the occurrence of sunshine from the intensity of their output. The device is equipped with three solar cells on a triangular prism oriented toward the celestial north pole – one on top and one on each of the southeast and southwest faces.

The output of the solar cells on each of the southeast and southwest faces includes direct solar irradiance and diffuse sky radiation. As the solar cell on the top is shaded from direct sunlight, its output can be considered equivalent to the level of diffuse sky radiation. By taking the difference between these outputs, an output value equivalent to the level of direct solar irradiance can be obtained. Solar-cell-type sunshine recorders are somewhat inferior in terms of accuracy to rotating mirror sunshine recorders; they are known to underestimate the sunshine duration in the morning and evening, during cloudy weather, and in the summer season when the sun’s elevation is high.

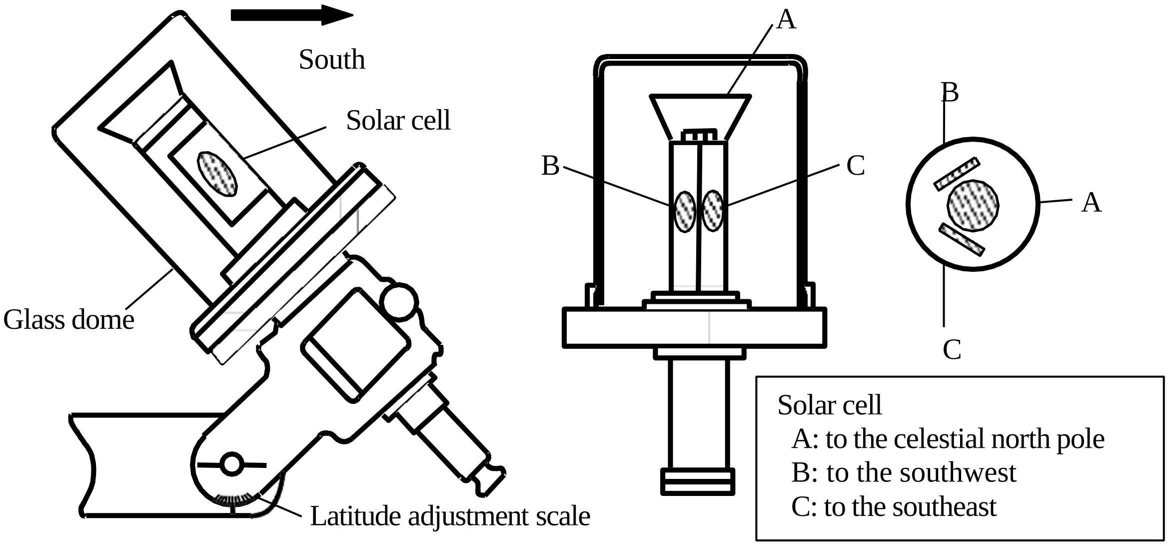


Figure 7.4 Solar-cell-type sunshine recorder

7.2 Measurement of Solar Radiation

7.2.1 Definitions and Units

(1) Definitions

Everything in nature emits electromagnetic energy, and solar radiation is energy emitted by the sun. The energy of extraterrestrial solar radiation is distributed over a wide continuous spectrum ranging from ultraviolet to infrared rays. In this spectrum, solar radiation in short wavelengths (0.29 to 3.0 μm) accounts for about 97 percent of the total energy. Figure 7.5 shows the spectrum distribution of solar radiation.

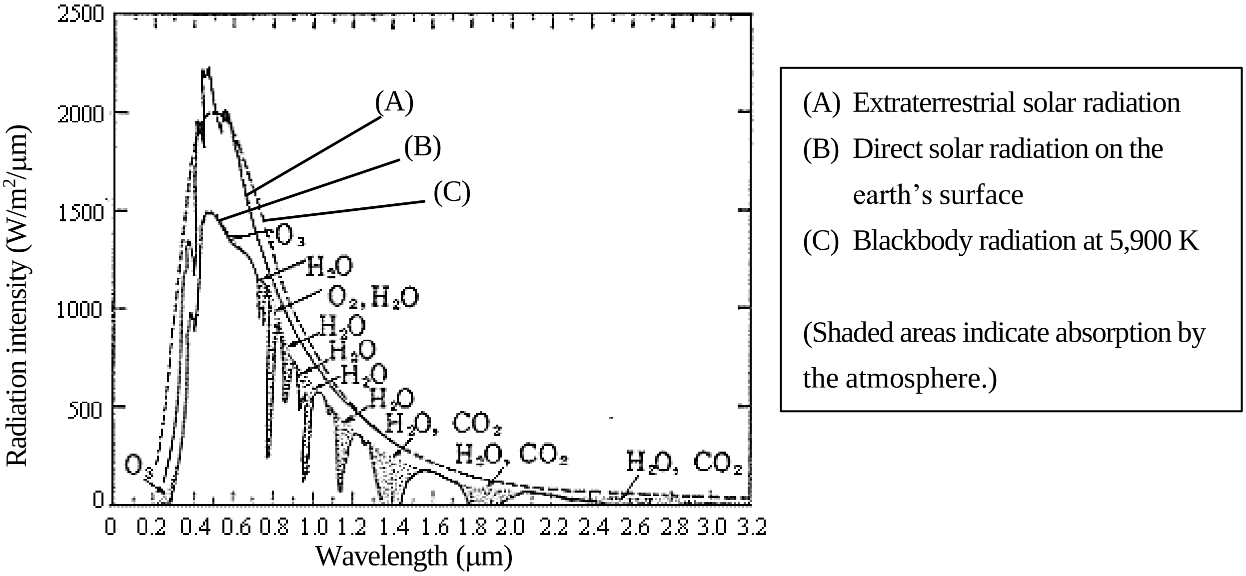


Figure 7.5 Spectrum distribution of solar radiation

Solar radiation is partly absorbed, scattered and reflected by molecules, aerosols, water vapor and clouds as it passes through the atmosphere. The direct solar beam arriving directly at the earth's surface is called direct solar radiation. The total amount of solar radiation falling on a horizontal surface (i.e. the direct solar beam plus diffuse solar radiation on a horizontal surface) is referred as global solar radiation.

Direct solar radiation is observed from sunrise to sunset, while global solar radiation is observed in the twilight before sunrise and after sunset, despite its diminished intensity at these times.

(2) Units

The solar irradiance is expressed in watts per square meter (W/m^2) and the total amount in joules per square meter (J/m^2). Conversion between the currently used unit (SI) and the former unit (calories) can be performed using the following formulae:

Solar irradiance: 1 kW/m^2 = 1.433 cal/cm^2/min

Total amount of solar radiation: 1 MJ/m^2 = 23.89 cal/cm^2

In Japan, the total amount of global solar radiation per day is about 20 MJ/m^2 in the summer in Okinawa and about 5 MJ/m^2 in the winter along the Sea of Japan. The value of direct solar irradiance is about 120 W/m^2 at around sunrise and sunset, and about 800 W/m^2 at around noon on a clear day in summer. Being aware of mean solar radiation levels in clear conditions for each season is useful for checking normal operation of instruments.

7.2.2 Solar Radiation Measuring Instruments (Radiometers)

A radiometer absorbs solar radiation at its sensor, transforms it into heat and measures the resulting amount of heat to ascertain the level of solar radiation. Methods of measuring heat include taking out heat flux as a temperature change (using a water flow pyrheliometer, a silver-disk pyrheliometer or a bimetallic pyranograph) or as a thermoelectromotive force (using a thermoelectric pyrheliometer or a thermoelectric pyranometer). In current operation, types using a thermopile are generally used.

The radiometers used for ordinary observation are pyrheliometers and pyranometers that measure direct solar radiation and global solar radiation, respectively, and these instruments are described in this section. For details of other radiometers such as measuring instruments for diffuse sky radiation and net radiation, refer to ”Guide to Meteorological Instruments and Observation Methods” and “Compendium of Lecture Notes on Meteorological Instruments for Training Class III and Class IV Meteorological Personnel” published by WMO.

7.2.2.1 Pyrheliometers

A pyrheliometer is used to measure direct solar radiation from the sun and its marginal periphery. To measure direct solar radiation correctly, its receiving surface must be arranged to be normal to the solar direction. For this reason, the instrument is usually mounted on a sun-tracking device called an equatorial mount.

The structure of an **Angstrom electrical compensation pyrheliometer** is shown in Figure 7.6 (a). This is a reliable instrument used to observe direct solar radiation, and has long been accepted as a working standard. However, its manual operation requires experience.

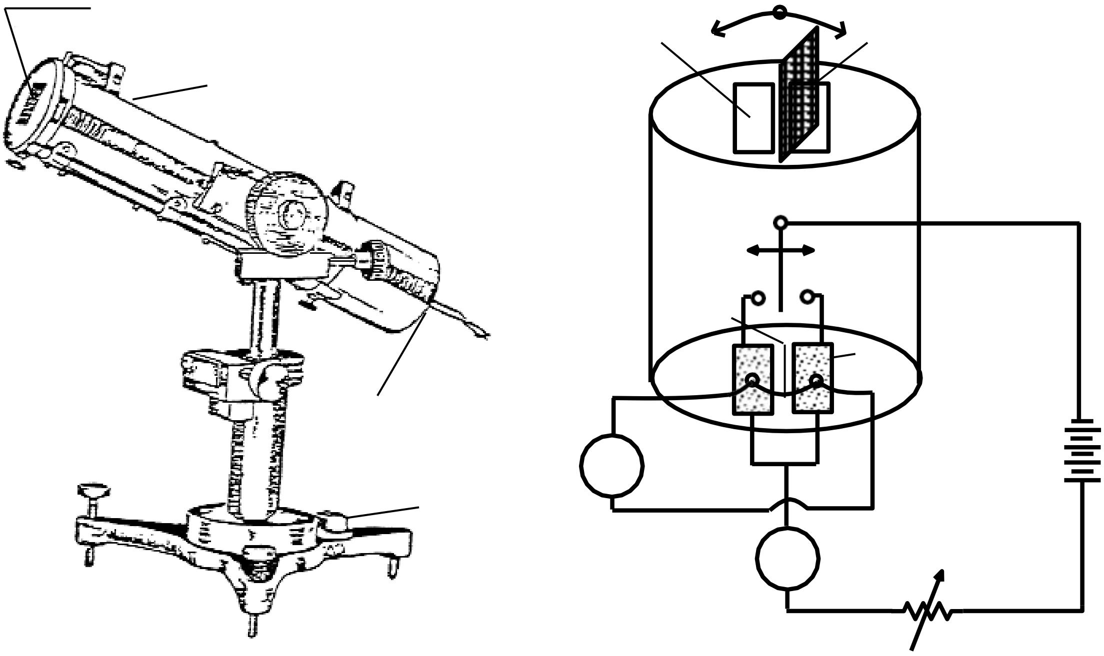


Figure 7.6 Angstrom electrical compensation pyrheliometer

(a) Structure

(b) Circuit

A: Aperture B: Battery C: Sensor surface D: Cylinder

P: Switch R: Variable resistor S: Shutter

T: Thermocouple G: Galvanometer mA: Ammeter

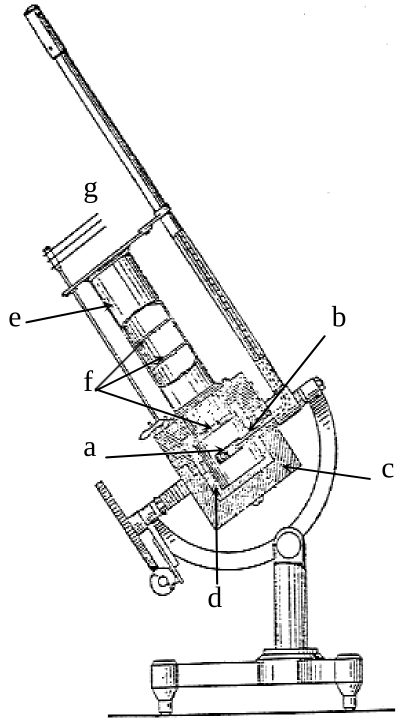
This pyrheliometer has a rectangular aperture, two manganin-strip sensors (20.0 mm × 2.0 mm × 0.02 mm) and several diaphragms to let only direct sunlight reach the sensor. The diaphragms are the same as those in the silver-disk pyrheliometer in Figure 7.7 and in the thermoelectric pyrheliometer in Figure 7.8. The sensor surface is painted optical black and has uniform absorption characteristics for short-wave radiation. A copper-constantan thermocouple is attached to the rear of each sensor strip, and the thermocouple is connected to a galvanometer. The sensor strips also work as electric resistors and generate heat when a current flows across them (see the principle drawing in Figure 7.6 (b)).

When solar irradiance is measured with this type of pyrheliometer, the small shutter on the front face of the cylinder shields one sensor strip from sunlight, allowing it to reach only the other sensor. A temperature difference is therefore produced between the two sensor strips because one absorbs solar radiation and the other does not, and a thermoelectromotive force proportional to this difference induces current flow through the galvanometer. Then, a current is supplied to the cooler sensor strip (the one shaded from solar radiation) until the pointer in the galvanometer indicates zero, at which point the temperature raised by solar radiation is compensated by Joule heat. A value for direct solar irradiance is obtained by converting the compensated current at this time. If S is the intensity of direct solar irradiance and i is the current, then

$$S = Ki^2,$$

where K is a constant intrinsic to the instrument and is determined from the size and electric resistance of the sensor strips and the absorption coefficient of their surfaces. The value of K is usually determined through comparison with an upper-class standard pyrheliometer.

The structure of a **silver-disk pyrheliometer** is shown in Figure 7.7. This instrument was developed as a portable version of a water flow pyrheliometer, which was the former primary standard.



a: Black-painted silver disk
b: Mercury-in-glass thermometer
c: Wooden container
d: Copper case
e: Cylinder
f: Diaphragm
g: Shutter

Figure 7.7 Silver-disk pyrheliometer

The sensing element is a silver disk measuring 28 mm in diameter with a thickness of 7 mm that is painted black on its radiation-receiving side. It has a hole from the periphery toward the center to allow insertion of the bulb of a high-precision mercury-in-glass thermometer. To maintain good thermal contact between the disk and the bulb, the hole is filled with a small amount of mercury. It is enclosed outside by a heat-insulating wooden container. The stem of the thermometer is bent in a right angle outside the wooden container and supported in a metallic protective tube. A cylinder with diaphragms inside is fitted in the wooden container to let direct solar radiation fall onto the silver disk. There is a metallic-plate shutter at the top end of the cylinder to block or allow the passage of solar radiation to the disk.

During the measurement phase, the disk is heated by solar radiation and its temperature rises. The intensity of this radiation is ascertained by measuring the temperature change of the disk between the measurement phase and the shading phase with the mercury-in-glass thermometer.

The structure of a **thermoelectric pyrheliometer** is shown in Figure 7.8. This instrument uses a thermopile at its sensor, and continuously delivers a thermoelectromotive force in proportion to the direct solar irradiance. While Angstrom electrical compensation pyrheliometers and silver-disk pyrheliometers have a structure that allows the outer air to come into direct contact with the sensor portion, this type has transparent optical glass in the aperture to make it suitable for use in all weather conditions. It is mounted on a sun-tracking device to enable outdoor installation for automatic operation by JMA.

There are several types of thermoelectric pyrheliometer, but their structures are similar. Figure 7.8 shows the structure of the one used by JMA. Copper-plated constantan wire is used as the thermopile in the sensor portion, which is attached to the bottom of the cylinder at right angles to the cylinder axis. The cylinder is fitted with diaphragms to direct sunlight to the sensor portion. It is made of a metallic block with high heat capacity and good thermal conductivity, and is enclosed in a polished intermediate cylinder and a silver-plated outer brass cylinder with high reflectivity to prevent rapid ambient temperature changes or outer wind from disturbing the heat flux in the radiation-sensing element. The cylinder is kept dry using a desiccant to prevent condensation on the inside of the aperture window.

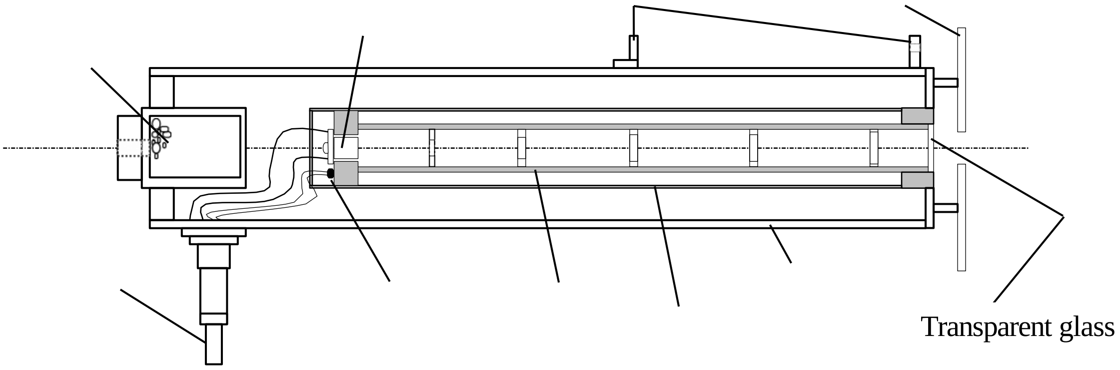


Figure 7.8 Thermoelectric pyrheliometer

In this pyrheliometer, a temperature difference is produced between the sensor surface (called the hot junction) and the reference temperature point, i.e., the metallic block of the inner cylinder (called the cold junction). As the temperature difference is proportional to the intensity of the radiation absorbed, the level of solar radiation can be derived by measuring the thermoelectromotive force from the thermopile. Since this type of pyrheliometer is a relative instrument, calibration should be performed to determine the instrumental factor through comparison with a standard instrument. As the thermoelectromotive force output depends on the unit’s temperature, the temperature inside the cylinder should be monitored to enable correction.

7.2.2.2 Pyranometers

A pyranometer is used to measure global solar radiation falling on a horizontal surface. Its sensor has a horizontal radiation-sensing surface that absorbs solar radiation energy from the whole sky (i.e. a solid angle of 2π sr) and transforms this energy into heat. Global solar radiation can be ascertained by measuring this heat energy. Most pyranometers in general use are now the thermopile type, although bimetallic pyranometers are occasionally found.

Thermoelectric pyranometers are shown in Figure 7.9. The instrument's radiation-sensing element has basically the same structure as that of a thermoelectric pyrheliometer. Another similarity is that the temperature difference derived between the radiation-sensing element (the hot junction) and the reflecting surface (the cold junction) that serves as a temperature reference point is expressed by a thermopile as an thermoelectromotive force. In the case of a pyranometer, methods of ascertaining the temperature difference are as follows:

1) Several pairs of thermocouples are connected in series to make a thermopile that detects the temperature difference between the black and white radiation-sensing surfaces (Figures 7.9 (a) and (c)).
2) The temperature difference between two black radiation-sensing surfaces with differing areas is detected by a thermopile.
3) The temperature difference between a radiation-sensing surface painted solid black and a metallic block with high heat capacity is detected by a thermopile (Figure 7.9 (b)).

A **bimetallic pyranograph** is shown in Figure 7.10. The radiation-sensing element (in the upper right of the figure) consists of two pairs of bimetals, one painted black and the other painted white, placed in opposite directions (face up and face down) and attached to a common metal plate at one end. At the other end, the white bimetallic strips are fixed to the frame of the pyranograph, and the black ones are connected to the recorder section via a transmission shaft. The deflection of the free edge of the black strips is transmitted to the recording pen through a magnifying system. When the air temperature changes, the black and white strips attached to the common plate at one end both bend by the same amount but in opposite directions. As a result, only the temperature difference attributed to solar radiation is transmitted to the recording pen.

Thermoelectric pyranometers and bimetallic pyranographs are both hermetically sealed in a glass dome to protect the sensor portion from wind and rain and prevent the sensor surface temperature from being disturbed by wind. A desiccant is placed in the dome to prevent condensation from forming on the inner surface. The glass allows the passage of solar radiation in wavelengths from about 0.3 to 3.0 μm – a range that covers most of the sun's radiation energy. Some models are equipped with a fan to prevent dust or frost, which greatly affect the amount of light received, from collecting on the dome's outer surface. It is necessary to check and clean the glass surface at regular intervals to ensure that the dome wall constantly allows the passage of solar radiation.

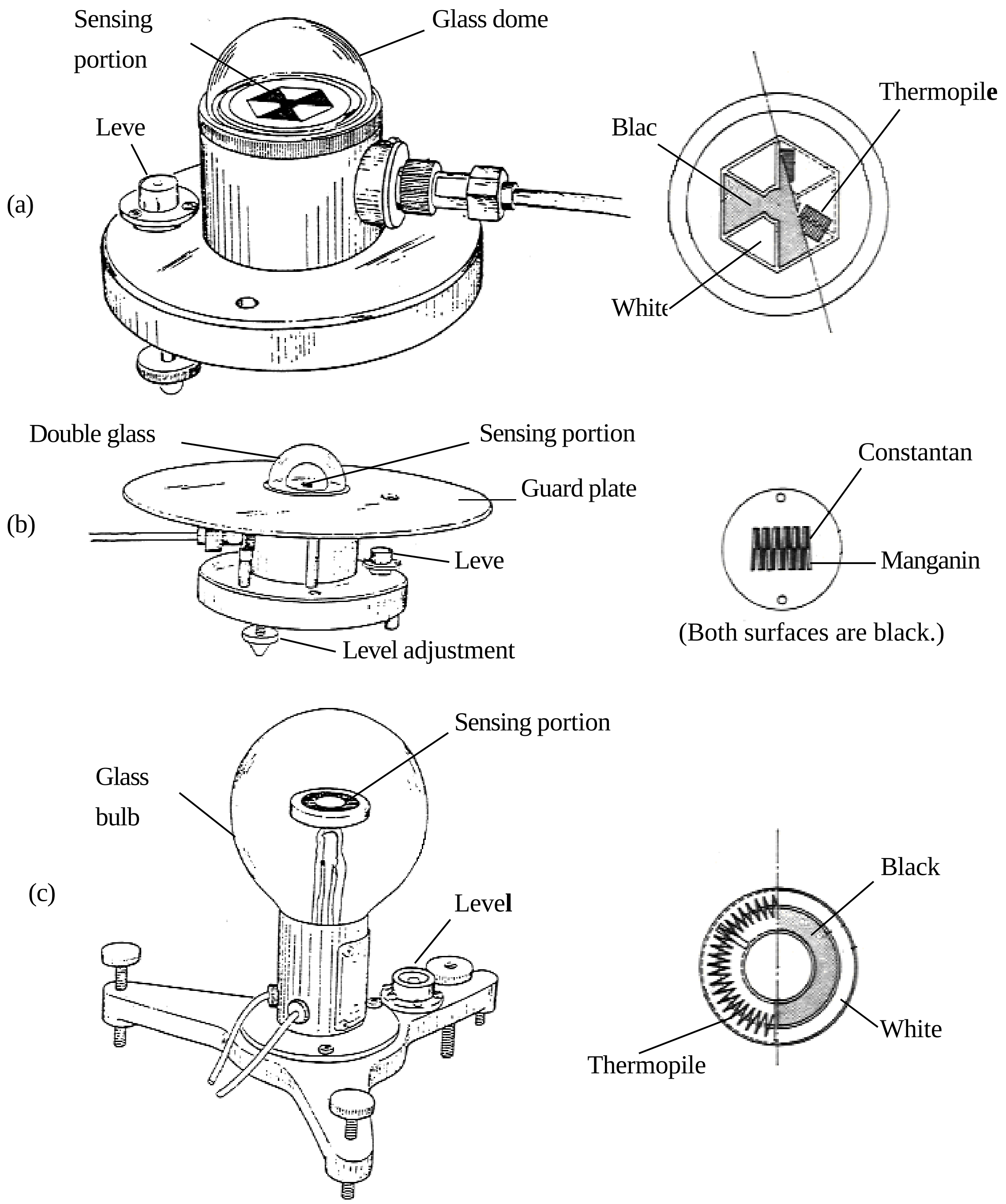


Figure 7.9 Thermoelectric pyranometer and sensing

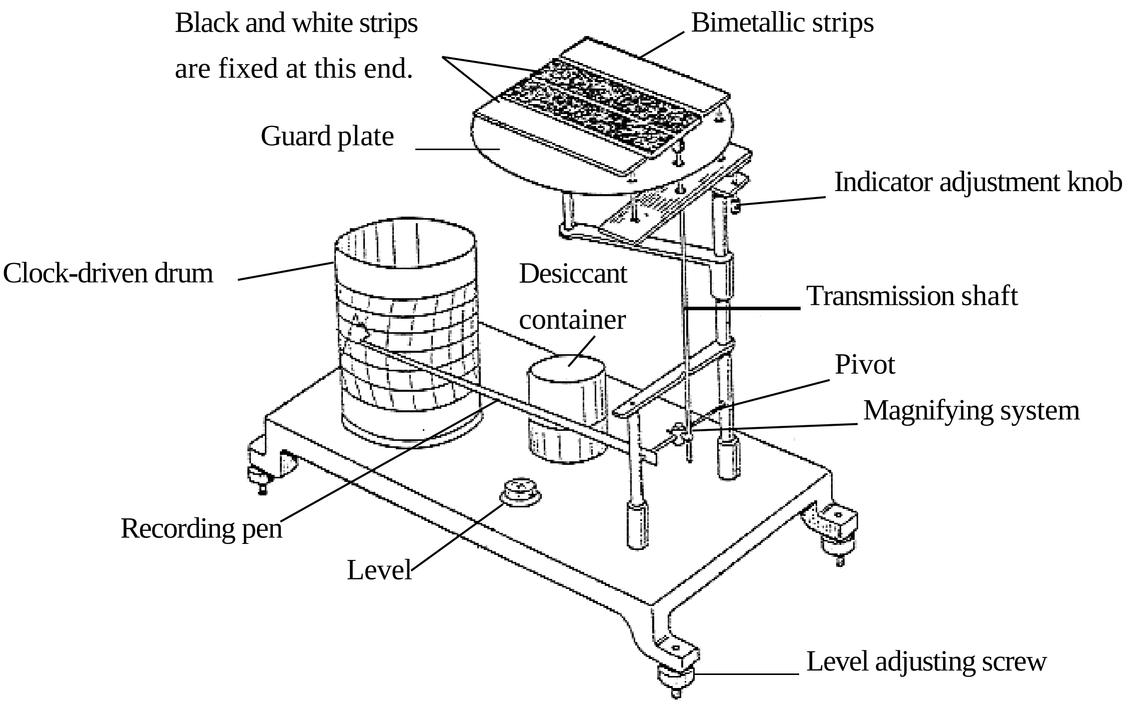


Figure 7.10 Bimetallic pyranograph

7.3 Sources of Errors

Radiometer measurement errors are attributed to sensitivity, response characteristics and other factors common to ordinary meteorological instruments. In addition to these influences, the following sources of measurement errors are also peculiar to radiometers:

(1) Wavelength Characteristics (for pyrheliometers and pyranometers)

The absorption coefficient of the radiation sensor surface and the transmission coefficient of the glass cover or glass dome of a radiometer should be constant for all wavelengths of solar radiation. In reality, however, these coefficients vary with wavelength. Since this wavelength characteristic differs slightly from radiometer to radiometer, observation errors occur when the energy distribution of solar radiation against wavelength varies with the sun's elevation or atmospheric conditions.

(2) Temperature Characteristics (for pyrheliometers and pyranometers)

As the thermoelectromotive force of a thermopile is nonlinear and the heat conductivity inside a radiometer depends on temperature, the sensitivity of these instruments varies and an error occurs when the ambient temperature and the temperature of the radiometer change.

(3) Characteristics against Elevation and Azimuth (for pyranometers)

The output of the ideal pyranometer decreases with lower sun elevation angles in proportion to cosZ (Z: zenith angle). In reality, however, output varies with the sun's elevation or azimuth due to the uneven absorption coefficient and with the shape of the radiation sensor surface. The characteristic may also deviate and errors may occur because of the uneven thickness, curvature or material of the glass cover. Usually, sensitivity rapidly decreases at an elevation angle of around 20 degrees or lower.

(4) Field of View (for pyrheliometers)

The field of view of a pyrheliometer is somewhat larger than the viewing angle of the sun. If the field of view differs, the extent of influence from diffuse sky radiation near the sun also differs. Pyrheliometers with different fields of view may make different observations depending on the turbidity of the atmosphere. (WMO recommends a total opening angle of five degrees.)

7.4 Siting and Exposure

Sunshine recorders and radiometers should be installed in a location where solar radiation is not shaded by trees or buildings in any season from sunrise to sunset and where there are no smoke emission sources. Pyranometers in particular should be installed at a site where the instrument is not influenced by intense reflected light from the wall surfaces of buildings. Usually, such instruments are installed on rooftops or towers, but the convenience of routine maintenance and checking tasks such as cleaning of the sensor part should be taken into consideration.

When installing a sunshine duration or solar radiation instrument, it must be set properly using a spirit level. It must also be oriented in the prescribed direction using the meridional plane as reference (for methods of determining the meridional direction, refer to Chapter 1) with its elevation angle set to the latitude of the site. It should be checked that the pyranometer's output does not fluctuate when the sensor rotates in clear weather.

7.5 Maintenance

Any dust, condensation, frost, ice or snow deposited on the windshield glass should be removed with a feather duster or soft cloth. Wash away any stubborn soiling with water while taking care not to damage the glass surface. As pyrheliometers have a small field of view, they are particularly sensitive to windshield glass soiling.

The desiccant in the sunshine recorder and the radiometer should be checked at regular intervals and replaced immediately once its function has deteriorated (the silica gel will turn pink). Any condensation forming on the inner surface of the windshield glass should be wiped off after detaching the glass, and the desiccant should be replaced. This maintenance should be carried out according to the indications of the instruction manual. However, if care is difficult (as in the case of a sealed instrument filled with dry air), contact the manufacturer to request repair.

If the paint on the radiation-sensing element of the radiometer has discolored or peeled, it should be repainted immediately.

As the indication from a radiometer fluctuates even in clear weather depending on the season and the time of day, it is difficult to determine whether the instrument is operating normally from the output value alone. Rough values of radiometer output in clear weather should be kept in mind, and the radiometer should be monitored to ensure that it is delivering the expected output value so that abnormalities can be detected at an early stage.

The sensor parts and the equatorial mount of a pyrheliometer are designed for all-weather usage, and continuous operation is usually possible. If potential damage from a severe storm is foreseen, operation should be stopped and the instrument should be brought indoors or protected with a cover.

7.6 Correlation between Sunshine Duration and Global Solar Radiation

The empirical correlation between sunshine duration and the amount of global solar radiation is as follows:

$$Q/Q_0 = a + bN/N_0,$$

where Q is the daily total amount of global solar radiation at the ground surface, Q_0 is the daily total amount of global solar radiation outside the atmosphere, N is the sunshine duration, N_0 is the possible sunshine duration, and a and b are constants.

The empirically obtained values of a and b vary depending on the location and month of observation. According to annual mean values obtained using Jordan sunshine recorders and pyranometers at five stations in Japan, the value of a ranges from 0.16 to 0.25, that of b ranges from 0.44 to 0.60, and the mean averaged values of a and b at the five stations are 0.22 and 0.52 respectively. These values may be affected by air pollution stemming from urban activity and factory operation. As the daily total amount of global solar radiation and the sunshine duration vary widely from day to day, daily totals averaged over a month are used to derive the values of a and b.

Although it is not possible to estimate the daily total amount of global solar radiation on a particular day from the sunshine duration using this method, it does enable rough estimation of a monthly value.

Chapter 4: Measurement of Humidity

CONTENTS

Chapter 4: Measurement of Humidity

3.1 Definitions and units

(1) Vapor pressure

Vapor pressure is the partial pressure of water vapor in the air, expressed in hPa.

(2) Saturation vapor pressure

Saturation vapor pressure is the vapor pressure that is in a thermodynamic equilibrium with the surface of water or ice, expressed in hPa.

(3) Dewpoint temperature

Dewpoint temperature is the air temperature at which the moist air saturates respect to water at a given pressure.

The dewpoint temperature is usually equal to or lower than the actual air temperature. The temperature at which moist air saturates with respect to ice is called the frost point temperature. the unit of these temperatures is ℃.

(4) Relative humidity

As shown below, relative humidity (H) is the ratio of the vapor pressure (e) of the moist air to its saturation vapor pressure (e_s) at its temperature, which is expressed in %.

$$H = (e/e_s) \times 100\ \%$$

$$H = (e/e_{sw}) \times 100\ \%$$

$$H = (e/e_{si}) \times 100\ \%$$

where H_w and e_{sw} are the saturation vapor pressure with respect to water, and H_i and e_{si} are the saturation vapor pressure with respect to ice, respectively.

3.2 Hygrometers

3.2.1 Psychrometer

(1) Principle of measurement

When water or ice covers the bulb of a thermometer (wet-bulb), latent heat is removed from the surface of the bulb as the water evaporates, and the wet-bulb temperature becomes lower than the air (dry-bulb) temperature. At a lower humidity, water evaporates more actively, so that the wet-bulb temperature lowerssharply. The aspirated psychrometer measures humidity by measuring the difference between the dry-bulb temperature and wet-bulb temperature.

(2) Structure and composition

The psychrometer consists of two thermometers of the same specifications, which are suspended side by side in the air. One of them measures the actual air (dry-bulb) temperature while the other, whose bulb is covered with a wet-bulb temperature.

Psychrometers are classified into the non-aspirated type psychrometer (portable aspirated psychrometers and sling psychrometers) and the aspirated type psychrometers (Assuman type aspirated psychrometer and JAM type aspirated psychrometers). Aspirated psychrometers are designed to keep the constant flow of air over around the bulbs. The structure and composition of the Assuman type aspirated psychrometer, which is commonly used in Japan, and described below.

Figure 3.1 shows the structure of the Assuman type aspirated psychrometer. The psychrometer consists of two enclosed scale type mercury thermometers, which can read temperature in increments of 0.1℃.

One of them is called a dry-bulb thermometer, which measures actual air temperature and the other is called a wet-bulb thermometer, which ismeasures the temperature of wet-bulb which covered with a wet sleeve. The wet sleeve is a white thin cotton cloth soaked with water.

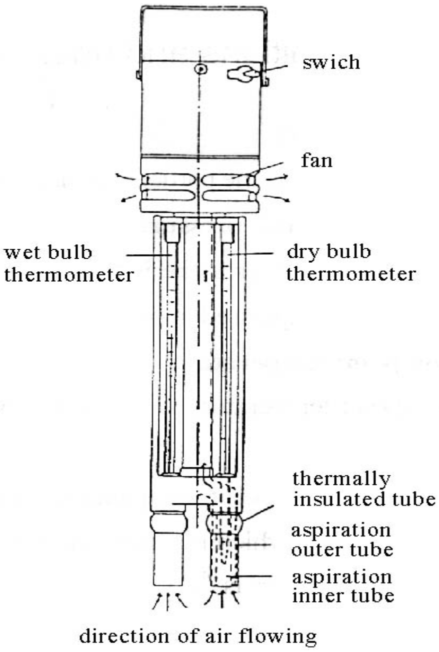


Figure 3.1Structure of Assuman type aspirated psychrometer

The external and internal cylinders of a metal aspiration tube protect the bulbs from precipitation and radiation of direct sunlight.

As shown in figure 3.1, air floe with a velocity of 2.5 m/s enters from the bottom with an electromotive fan or a spring fan. The time constant of the psychrometer is about 40 seconds.

A squirt is used to feed water to the wet sleeve of the wet-bulb or to suck excess water from it.

(3) Psychrometric formula and psychrometric table

When the air steadily flows around the wet-bulb, the wet-bulb temperature falls below the air temperature by water evaporation from the surface of the wet-bulb. When the heat flow moving into the wet-bulb from the ambient air has reached equilibrium with the latent heat flow removed from the wet-bulb by evaporation, the following equation, called the Sprung psychrometric formula, is derived with the Assuman type aspirated psychrometer,

$$e= e_w - (A/755)\ p\ (t-t_w) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where

A/755: Psychrometer constant, A is 0.50 when the wet-bulb is not frozen and 0.44 when it is frozen.

e: Vapor pressure	hPa
e_w: Saturation vapor pressure	hPa

p: Atmospheric pressure hPa
t: Dry-bulb temperature ℃
t_w: Wet-bulb temperature ℃

Vapor pressure is calculated with this equation (1). Table 3.1 and Table 3.2 show the saturation vapor pressure for water and ice as a function of temperature.

The second term on the right side of the equation (1) is calculated a function of p and ($t-t_w$), which is tabulated as the vapor pressure table in Table 3.3 and Table 3.4 for the unfrozen and frozen wet-bulb.

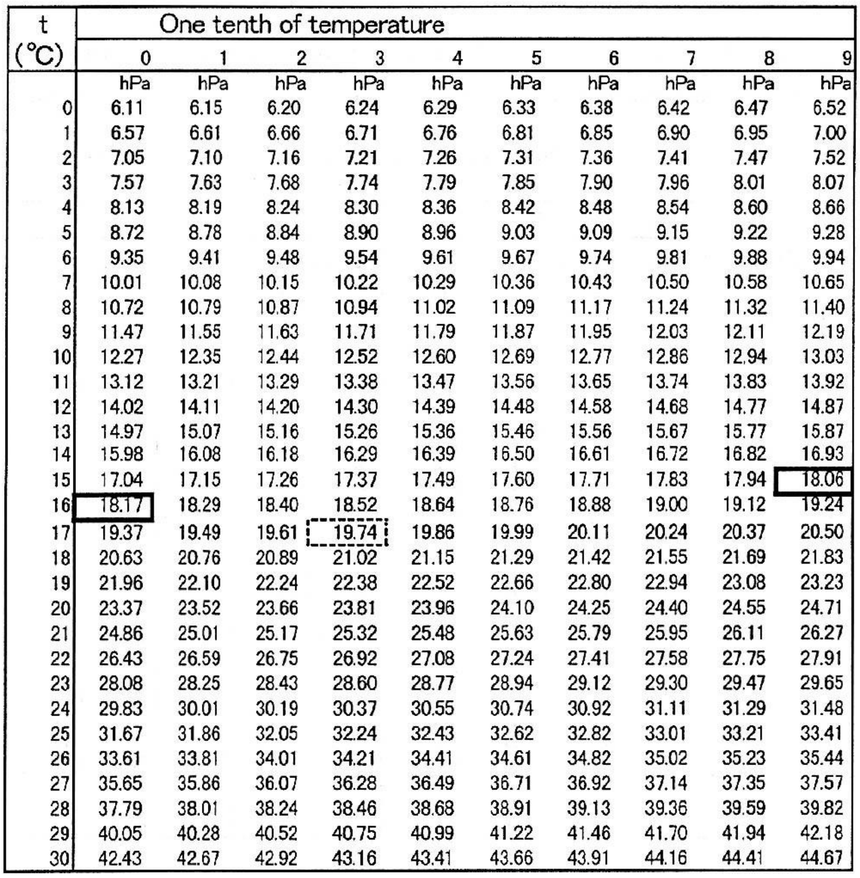
(4) Calculations of vapor pressure, dewpoint temperature, and relative humidity

The vapor pressure, dewpoint temperature, and relative humidity are calculated from the measurement with the aspirated psychrometer using the tables described above.

Calculation of vapor pressure

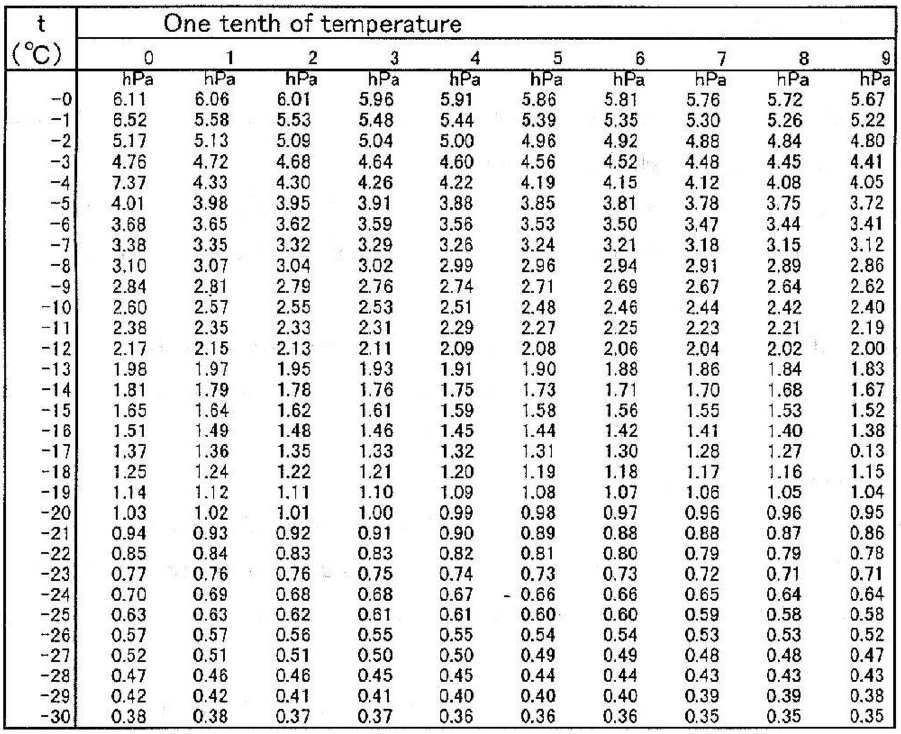
1) Make correction of the instrumental error of the dry-and wet-bulb thermometer.
2) Using Table 3.1 or 3.2, determine the value of the saturation vapor pressure for water (e_w) or ice (e_i) as a function of the wet-bulb thermometer temperature (t_w).

Table 3.1 Saturation vapor pressure for water



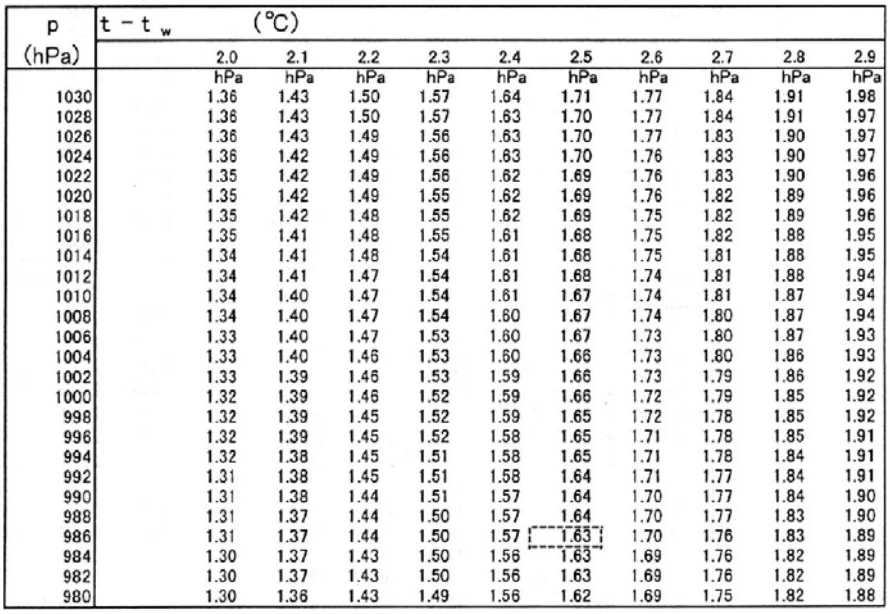
t (℃)	One tenth of temperature									
	0	1	2	3	4	5	6	7	8	9
	hPa	hPa	hPa	hPa	hPa	hPa	hPa	hPa	hPa	hPa
0	6.11	6.15	6.20	6.24	6.29	6.33	6.38	6.42	6.47	6.52
1	6.57	6.61	6.66	6.71	6.76	6.81	6.85	6.90	6.95	7.00
2	7.05	7.10	7.16	7.21	7.26	7.31	7.36	7.41	7.47	7.52
3	7.57	7.63	7.68	7.74	7.79	7.85	7.90	7.96	8.01	8.07
4	8.13	8.19	8.24	8.30	8.36	8.42	8.48	8.54	8.60	8.66
5	8.72	8.78	8.84	8.90	8.96	9.03	9.09	9.15	9.22	9.28
6	9.35	9.41	9.48	9.54	9.61	9.67	9.74	9.81	9.88	9.94
7	10.01	10.08	10.15	10.22	10.29	10.36	10.43	10.50	10.58	10.65
8	10.72	10.79	10.87	10.94	11.02	11.09	11.17	11.24	11.32	11.40
9	11.47	11.55	11.63	11.71	11.79	11.87	11.95	12.03	12.11	12.19
10	12.27	12.35	12.44	12.52	12.60	12.69	12.77	12.86	12.94	13.03
11	13.12	13.21	13.29	13.38	13.47	13.56	13.65	13.74	13.83	13.92
12	14.02	14.11	14.20	14.30	14.39	14.48	14.58	14.68	14.77	14.87
13	14.97	15.07	15.16	15.26	15.36	15.46	15.56	15.67	15.77	15.87
14	15.98	16.08	16.18	16.29	16.39	16.50	16.61	16.72	16.82	16.93
15	17.04	17.15	17.26	17.37	17.49	17.60	17.71	17.83	17.94	18.06
16	18.17	18.29	18.40	18.52	18.64	18.76	18.88	19.00	19.12	19.24
17	19.37	19.49	19.61	19.74	19.86	19.99	20.11	20.24	20.37	20.50
18	20.63	20.76	20.89	21.02	21.15	21.29	21.42	21.55	21.69	21.83
19	21.96	22.10	22.24	22.38	22.52	22.66	22.80	22.94	23.08	23.23
20	23.37	23.52	23.66	23.81	23.96	24.10	24.25	24.40	24.55	24.71
21	24.86	25.01	25.17	25.32	25.48	25.63	25.79	25.95	26.11	26.27
22	26.43	26.59	26.75	26.92	27.08	27.24	27.41	27.58	27.75	27.91
23	28.08	28.25	28.43	28.60	28.77	28.94	29.12	29.30	29.47	29.65
24	29.83	30.01	30.19	30.37	30.55	30.74	30.92	31.11	31.29	31.48
25	31.67	31.86	32.05	32.24	32.43	32.62	32.82	33.01	33.21	33.41
26	33.61	33.81	34.01	34.21	34.41	34.61	34.82	35.02	35.23	35.44
27	35.65	35.86	36.07	36.28	36.49	36.71	36.92	37.14	37.35	37.57
28	37.79	38.01	38.24	38.46	38.68	38.91	39.13	39.36	39.59	39.82
29	40.05	40.28	40.52	40.75	40.99	41.22	41.46	41.70	41.94	42.18
30	42.43	42.67	42.92	43.16	43.41	43.66	43.91	44.16	44.41	44.67

Table 3.2 Saturation vapor pressure for ice



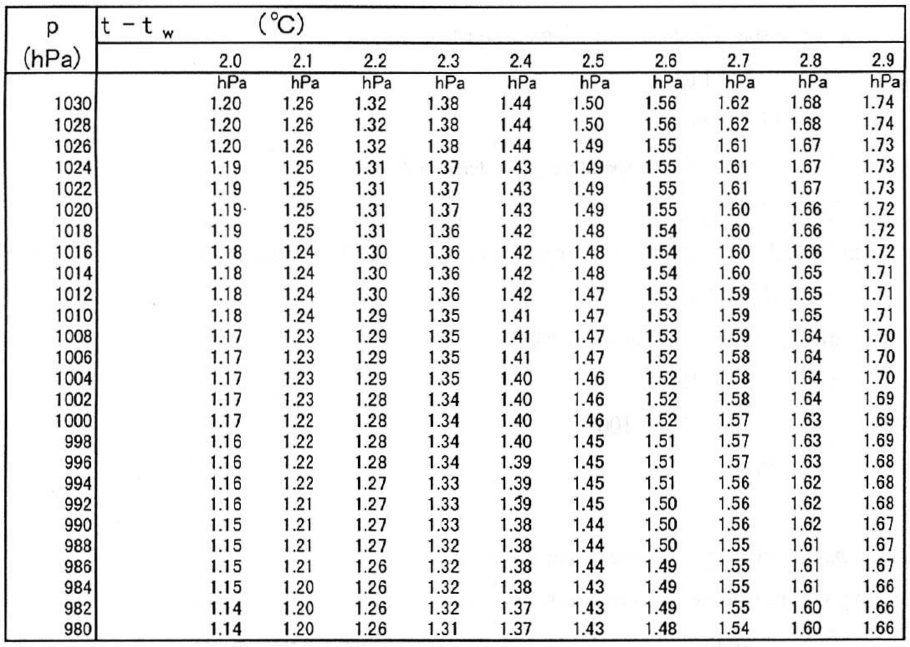
t (°C)	One tenth of temperature									
	0	1	2	3	4	5	6	7	8	9
	hPa	hPa	hPa	hPa	hPa	hPa	hPa	hPa	hPa	hPa
−0	6.11	6.06	6.01	5.96	5.91	5.86	5.81	5.76	5.72	5.67
−1	6.52	5.58	5.53	5.48	5.44	5.39	5.35	5.30	5.26	5.22
−2	5.17	5.13	5.09	5.04	5.00	4.96	4.92	4.88	4.84	4.80
−3	4.76	4.72	4.68	4.64	4.60	4.56	4.52	4.48	4.45	4.41
−4	7.37	4.33	4.30	4.26	4.22	4.19	4.15	4.12	4.08	4.05
−5	4.01	3.98	3.95	3.91	3.88	3.85	3.81	3.78	3.75	3.72
−6	3.68	3.65	3.62	3.59	3.56	3.53	3.50	3.47	3.44	3.41
−7	3.38	3.35	3.32	3.29	3.26	3.24	3.21	3.18	3.15	3.12
−8	3.10	3.07	3.04	3.02	2.99	2.96	2.94	2.91	2.89	2.86
−9	2.84	2.81	2.79	2.76	2.74	2.71	2.69	2.67	2.64	2.62
−10	2.60	2.57	2.55	2.53	2.51	2.48	2.46	2.44	2.42	2.40
−11	2.38	2.35	2.33	2.31	2.29	2.27	2.25	2.23	2.21	2.19
−12	2.17	2.15	2.13	2.11	2.09	2.08	2.06	2.04	2.02	2.00
−13	1.98	1.97	1.95	1.93	1.91	1.90	1.88	1.86	1.84	1.83
−14	1.81	1.79	1.78	1.76	1.75	1.73	1.71	1.70	1.68	1.67
−15	1.65	1.64	1.62	1.61	1.59	1.58	1.56	1.55	1.53	1.52
−16	1.51	1.49	1.48	1.46	1.45	1.44	1.42	1.41	1.40	1.38
−17	1.37	1.36	1.35	1.33	1.32	1.31	1.30	1.28	1.27	0.13
−18	1.25	1.24	1.22	1.21	1.20	1.19	1.18	1.17	1.16	1.15
−19	1.14	1.12	1.11	1.10	1.09	1.08	1.07	1.06	1.05	1.04
−20	1.03	1.02	1.01	1.00	0.99	0.98	0.97	0.96	0.96	0.95
−21	0.94	0.93	0.92	0.91	0.90	0.89	0.88	0.88	0.87	0.86
−22	0.85	0.84	0.83	0.83	0.82	0.81	0.80	0.79	0.79	0.78
−23	0.77	0.76	0.76	0.75	0.74	0.73	0.73	0.72	0.71	0.71
−24	0.70	0.69	0.68	0.68	0.67	0.66	0.66	0.65	0.64	0.64
−25	0.63	0.63	0.62	0.61	0.61	0.60	0.60	0.59	0.58	0.58
−26	0.57	0.57	0.56	0.55	0.55	0.54	0.54	0.53	0.53	0.52
−27	0.52	0.51	0.51	0.50	0.50	0.49	0.49	0.48	0.48	0.47
−28	0.47	0.46	0.46	0.45	0.45	0.44	0.44	0.43	0.43	0.43
−29	0.42	0.42	0.41	0.41	0.40	0.40	0.40	0.39	0.39	0.38
−30	0.38	0.38	0.37	0.37	0.36	0.36	0.36	0.35	0.35	0.35

Table 3.3 Vapor pressure for unfrozen wet-bulb



p (hPa)	$t - t_w$ (°C)									
	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9
	hPa	hPa	hPa	hPa	hPa	hPa	hPa	hPa	hPa	hPa
1030	1.36	1.43	1.50	1.57	1.64	1.71	1.77	1.84	1.91	1.98
1028	1.36	1.43	1.50	1.57	1.63	1.70	1.77	1.84	1.91	1.97
1026	1.36	1.43	1.49	1.56	1.63	1.70	1.77	1.83	1.90	1.97
1024	1.36	1.42	1.49	1.56	1.63	1.70	1.76	1.83	1.90	1.97
1022	1.35	1.42	1.49	1.56	1.62	1.69	1.76	1.83	1.90	1.96
1020	1.35	1.42	1.49	1.55	1.62	1.69	1.76	1.82	1.89	1.96
1018	1.35	1.42	1.48	1.55	1.62	1.69	1.75	1.82	1.89	1.96
1016	1.35	1.41	1.48	1.55	1.61	1.68	1.75	1.82	1.88	1.95
1014	1.34	1.41	1.48	1.54	1.61	1.68	1.75	1.81	1.88	1.95
1012	1.34	1.41	1.47	1.54	1.61	1.68	1.74	1.81	1.88	1.94
1010	1.34	1.40	1.47	1.54	1.61	1.67	1.74	1.81	1.87	1.94
1008	1.34	1.40	1.47	1.54	1.60	1.67	1.74	1.80	1.87	1.94
1006	1.33	1.40	1.47	1.53	1.60	1.67	1.73	1.80	1.87	1.93
1004	1.33	1.40	1.46	1.53	1.60	1.66	1.73	1.80	1.86	1.93
1002	1.33	1.39	1.46	1.53	1.59	1.66	1.73	1.79	1.86	1.92
1000	1.32	1.39	1.46	1.52	1.59	1.66	1.72	1.79	1.85	1.92
998	1.32	1.39	1.45	1.52	1.59	1.65	1.72	1.78	1.85	1.92
996	1.32	1.39	1.45	1.52	1.58	1.65	1.71	1.78	1.85	1.91
994	1.32	1.38	1.45	1.51	1.58	1.65	1.71	1.78	1.84	1.91
992	1.31	1.38	1.45	1.51	1.58	1.64	1.71	1.77	1.84	1.91
990	1.31	1.38	1.44	1.51	1.57	1.64	1.70	1.77	1.84	1.90
988	1.31	1.37	1.44	1.50	1.57	1.64	1.70	1.77	1.83	1.90
986	1.31	1.37	1.44	1.50	1.57	1.63	1.70	1.76	1.83	1.89
984	1.30	1.37	1.43	1.50	1.56	1.63	1.69	1.76	1.82	1.89
982	1.30	1.37	1.43	1.50	1.56	1.63	1.69	1.76	1.82	1.89
980	1.30	1.36	1.43	1.49	1.56	1.62	1.69	1.75	1.82	1.88

Table 3.4 Vapor pressure for frozen wet bulb



p (hPa)	$t - t_w$ (°C)									
	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9
	hPa	hPa	hPa	hPa	hPa	hPa	hPa	hPa	hPa	hPa
1030	1.20	1.26	1.32	1.38	1.44	1.50	1.56	1.62	1.68	1.74
1028	1.20	1.26	1.32	1.38	1.44	1.50	1.56	1.62	1.68	1.74
1026	1.20	1.26	1.32	1.38	1.44	1.49	1.55	1.61	1.67	1.73
1024	1.19	1.25	1.31	1.37	1.43	1.49	1.55	1.61	1.67	1.73
1022	1.19	1.25	1.31	1.37	1.43	1.49	1.55	1.61	1.67	1.73
1020	1.19	1.25	1.31	1.37	1.43	1.49	1.55	1.60	1.66	1.72
1018	1.19	1.25	1.31	1.36	1.42	1.48	1.54	1.60	1.66	1.72
1016	1.18	1.24	1.30	1.36	1.42	1.48	1.54	1.60	1.66	1.72
1014	1.18	1.24	1.30	1.36	1.42	1.48	1.54	1.60	1.65	1.71
1012	1.18	1.24	1.30	1.36	1.42	1.47	1.53	1.59	1.65	1.71
1010	1.18	1.24	1.29	1.35	1.41	1.47	1.53	1.59	1.65	1.71
1008	1.17	1.23	1.29	1.35	1.41	1.47	1.53	1.59	1.64	1.70
1006	1.17	1.23	1.29	1.35	1.41	1.47	1.52	1.58	1.64	1.70
1004	1.17	1.23	1.29	1.35	1.40	1.46	1.52	1.58	1.64	1.70
1002	1.17	1.23	1.28	1.34	1.40	1.46	1.52	1.58	1.64	1.69
1000	1.17	1.22	1.28	1.34	1.40	1.46	1.52	1.57	1.63	1.69
998	1.16	1.22	1.28	1.34	1.40	1.45	1.51	1.57	1.63	1.69
996	1.16	1.22	1.28	1.34	1.39	1.45	1.51	1.57	1.63	1.68
994	1.16	1.22	1.27	1.33	1.39	1.45	1.51	1.56	1.62	1.68
992	1.16	1.21	1.27	1.33	1.39	1.45	1.50	1.56	1.62	1.68
990	1.15	1.21	1.27	1.33	1.38	1.44	1.50	1.56	1.62	1.67
988	1.15	1.21	1.27	1.32	1.38	1.44	1.50	1.55	1.61	1.67
986	1.15	1.21	1.26	1.32	1.38	1.44	1.49	1.55	1.61	1.67
984	1.15	1.20	1.26	1.32	1.38	1.43	1.49	1.55	1.61	1.66
982	1.14	1.20	1.26	1.32	1.37	1.43	1.49	1.55	1.60	1.66
980	1.14	1.20	1.26	1.31	1.37	1.43	1.48	1.54	1.60	1.66

3) Using Table 3.3 and 3.4 calculate the second term on the right side of the equation (1) as a function of atmospheric pressure (p) and (t-t_w), where t is the dry-bulb thermometer temperature.
4) The vapor pressure e is obtained by making a subtraction between the above two values.

Determination of dewpoint temperature

The dewpoint temperature is determined as a function of the vapor pressure in Table 3.1. If the vapor pressure is too low to find out in Table 3.1, calculate the dewpoint pressure by interpolation to 1/100. If the vapor pressure is equal to or less than 0.05 hPa, consider the dewpoint temperature to be less than –50℃.

Calculation of relative humidity

Determine the saturation vapor pressure (e_w), as a function of (t_w) and then calculate the ratio of the vapor pressure (e) to (e_w). If the vapor pressure is determined to be a minus value, consider the relative humidity to be zero.

Example of calculation of relative humidity is as follows.

Dry-bulb thermometer reading	t_{dR}=19.7 ℃
Instrumental error	$t_{dl,}$ =-0.1 ℃
Dry-bulb thermometer temperature	t =19.8 ℃
Wet-bulb thermometer temperature	t_{dw}=17.3 ℃
Instrumental error	$t_{wl,}$= 0.0 ℃
Wet-bulb thermometer temperature	t_w =17.3 ℃
Atmospheric pressure	p =985.2 hPa

Using Table 3.1, the saturation vapor pressure e_w corresponding to t_w =17.3 ℃ is :

$$e_w=19.74 \text{ hPa}$$

Using Table 3.3, the second term on the right side of the equation (1), $(Ap\ (t- t_w)/755)$ is calculated using the value of $(t- t_w)=2.5$℃ and $p=985.2$ hPa

$$Ap\ (t- t_w)/755=1.63 \text{ hPa},$$

where $A=0.50$ is used.

Thus the vapor pressure e is calculated using the equation (1),

$$\begin{aligned} e&=19.74-1.63 \\ &=18.11 \text{ hPa}. \end{aligned}$$

Using Table 3.1, the dewpoint temperature t_d is determined to be

$$t_d=15.9℃.$$

Using again Table 3.1, the saturation vapor pressure e_w corresponding to the air temperature $t =19.8$ ℃ is :

$$e_w=23.08 \text{ hPa}$$

Thus the relative humidity is calculate as follows:

$$\begin{aligned} H&= (e/e_w)\times 100 \\ &=(18.11/23.08)\times 100 \\ &=78\%. \end{aligned}$$

(5) Precautions for using the aspirated psychrometer

1) Supply water to the wet-bulb with distilled water or soft water, using the squirt.
   If the air temperature is 0℃ or less, the water of the wet-sleeve may be frozen. In that case, make the icy membrane around the wet-bulb as thin as possible, using warmed water.

<Notes>

   a) Do not supply the wet-bulb with too much water. If too much water is supplied to the bulb suck excess water by squirt or by attaching a brush to the bottom of the bulb. Do not wet the inside of the aspiration tube.
   b) Use water of the air temperature.
   c) In the case that the air temperature is high and the humidity is low, the wet-bulb may dry up by the time when the observer reads the temperature. In such a case, supply water to the wet-bulb repeatedly.

2) Operate the fan for aspiration to make the air flow around the bulbs
3) Before reading a wet-bulb temperature, it is necessary that the indication is stable.
   When the wet-bulb temperature is slightly below 0℃, the water of the wet-sleeve may not freeze but be super cooled. Thus when the temperature is around or less than 0℃, see carefully the state of the wet-bulb to find whether the wet-bulb is frozen or super cooled and use the appropriate saturation vapor pressure table. To determine whether the wet-bulb is frozen or super cooled, gently touch the surface of the wet-bulb with something like a needle. Degree of gloss on the surface of the wet-bulb is also useful to check if the wet-bulb is frozen.

<Notes>

   a) The time for aspiration required to stabilize the reading is typically five minutes if the temperature is 0℃ or higher. If the temperature is less than 0℃, an aspiration time longer than five minutes will be needed.

b) If then evaporation from the wet-bulb is a little because of high humidity or if the wet-bulb temperature is slightly below 0℃, it would take 10 to 20 minutes for the stabilization of reading.

c) If the wet-bulb temperature is much lower than 0℃, make calculations using the saturation vapor pressure for ice.

4) Read the dry-bulb temperature.

5) Read the wet-bulb temperature.

6) Read the dry-bulb temperature and wet-bulb temperature again.

<Notes>

a) In the foggy condition, the wet-bulb temperature may be higher than the dry-bulb temperature. In such a case, consider the dry-bulb temperature to be the wet-bulb temperature.

b) If the first reading and the second one are different, repeat the reading again.

(6) Sources to cause errors

a) The psychrometer constant A in the psychrometric formula varies, depending on whether the wet-bulb is frozen or not and the incorrect determination of the wet-bulb leads to errors. So the state of the wet-bulb should be checked especially in cold conditions before the calculation.

b) As the temperature becomes lower, air contains less vapor, and the saturation pressure becomes lower. So the wet-bulb temperature reading error affects the vapor pressure calculations more significantly. Because of this, much care is needed with reading the psychrometer at low temperatures.

c) A portable aspirated psychrometer which is not subjected to forced aspiration is significantly affected by the natural wind. When a portable aspirated psychrometer is used in a thermometer shelter and the natural wind speed ranges from 0.3 to 4.0 m/s, the error in humidity may become as high as 7% because the aspiration velocity in the shelter is lower than the wind speed out of the shelter.

d) The wet-bulb temperature is affected by oil on the wet sleeve as well as by any impurities, such as salt dissolved in the water. A dirty wet sleeve also prevents correct measurement. Deposits of dirt on the wet-bulb after the prolonged use may cause errors.

e) Generally, the dry-bulb and wet-bulb thermometers have the same size and shape. Because the wet-bulb has higher thermal conductivity, it responds to changes in air temperature a little more quickly than the dry-bulb. Normally, when the air temperature changes, the wet-bulb firstly responds, causing a temporary change of humidity indication. On the other hand, the wet-bulb responds less quickly when a thick icy membrane is formed on the bulb.

(7) Maintenance

Routine maintenance

Make sure the aspiration fan in running properly at every observation.

Periodic maintenance

a) If the wet sleeve becomes dirty, replace it with a new one. In Japan, the sleeve is replaced twice a month. However, the sleeve must be replaced more frequently if it is placed in the environment with much dirt or in the sea breeze zone.

b) Wash off deposits on the wet-bulb when the wet sleeve is replaced.

(8) Calibration

The psychrometer is calibrated by measuring temperature, because it consists of thermometers. The aspiration velocity of the aspirated psychrometer is measured by the static pressure method as illustrated in Figure 3.2. At first, a hole is made in the aspiration tube where a thermometer bulb is placed. Next, the hole is connected to a manometer using a probe like a Pitot tube or a vinyl tube. Then air is led to flow through the aspiration tube, and the differential pressure is measured using the manometer to find the wind velocity. The relationship between the manometer differential pressure and the wind velocity is determined in a wind tunnel in advance.

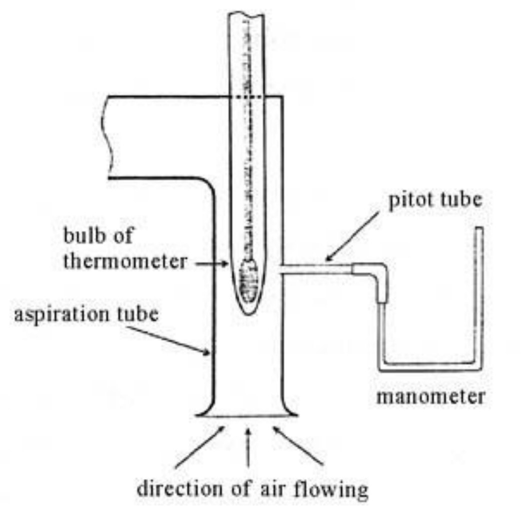


Figure 3.2 Measurement of static pressure

(9) Repair

A broken glass thermometer must be replaced since it cannot be repaired. Refer to the instruction manual of the aspirator to repair the aspirator motor.

(10) Transportation and installation

Transportation [See 1.5(3), "Transportation of instruments"]

a) Wrap the glass parts of the psychrometer in a soft cloth, and wrap the entire psychrometer in wrapping paper.

b) Place the psychrometer in a solid box and indicate "HANDLE WITH CARE" on the box.

Installation [See 1.5(4), "Siting and Exposure"]

a) Install the psychrometer in a wet-ventilated location protected from direct sunlight. Keep the psychrometer away from sources of heat radiation, such as a concrete wall exposed to direct sunlight.

b) Do no place the psychrometer near heat sources and vapor sources.

c) Place the bulbs about 1.2 to 2 ,m above the ground.

d) Suspend the psychrometer from a hanger on the supporting pole. Take readings of the psychrometer in its suspended position or in the position that the aspiration entrance is inclined windward.

e) place a non-aspirated type psychrometer in a thermometer shelter to protect it from precipitation, direct sunlight and radiation.

3.2.2 Hair hygrometer

(1) Principle of measurement and structure

The hair hygrometer uses the characteristic of the hair that its length expands or shrinks response to the relative humidity. the dimensions of various organic materials vary with their moisture content. A humidity change takes an effect on the moisture content in such materials. The length of human hair from which liquid are removed increases by 2 to 2.5% when relative humidity changes by 0 to 100%. Different types of human hair show different changes in length. However, there is still a relationship between the length of hair and relative humidity.

The hair hygrograph is a hair hygrometer to which a clock-driven drum is installed to record humidity no a recording chart.

When the humidity in the air changes, a hair bundle ④ expands or shrinks, so hair joint metal attached to a lever ⑩ moves, making a rotation of a main can ③. The weight of a pen arm attached to the shaft ⑥ give a downward moment to the sub cam ④ .

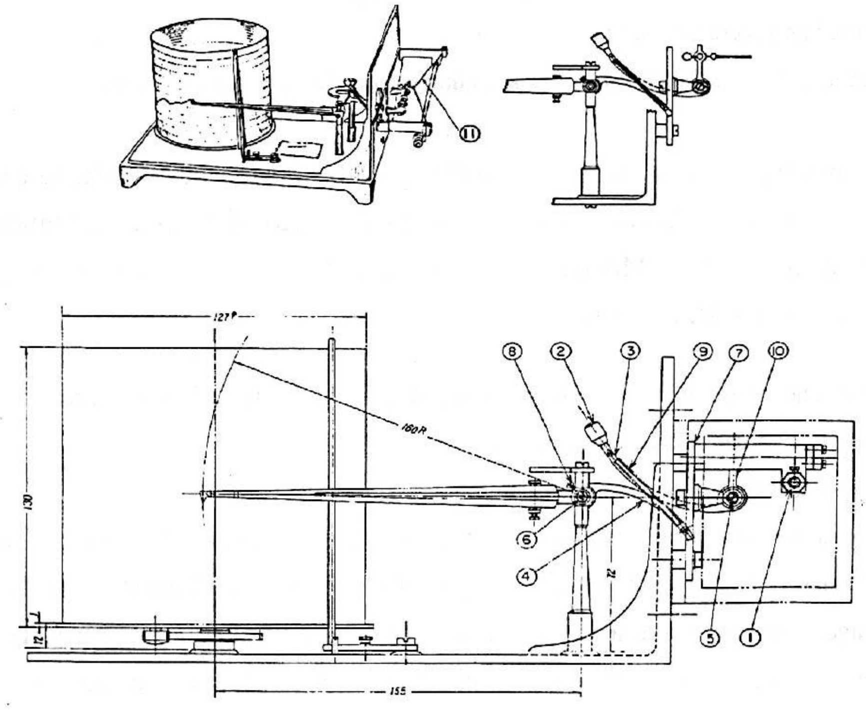


Figure 3.3 Structure of hair hygrograph

①Indicator adjusting screw ②Weight ③Main cam
④Sub cam ⑤Rotation axis for main cam ⑥Rotation axis for sub cam
⑦Plate attaching sensor part of humidity ⑧Screw attaching sub cam ⑨Connecting spring
⑩lever ④Hair bundle

The plumb ② of the main cam balances with moment
and a small change of the hair bundle ④ is magnified to the movement of the pen.

Since the length of the hair increases almost logarithmically with the increase of humidity, changes in humidity are not indicated correctly when the elongation of hair is linearly recorded. The hair hygrometer uses two special cams to put graduations on the hygrometer at equal intervals. A spring ⑨ joints cams ③ and ④ to prevent them from each other. The movement of the main cam ③ differ from that of the sub cam ④ depending on the position of the contact point of these two cams. At low humidity, the movement of the sub cam ④ is less than that of the main cam ③. As humidity increases, the movement of the sub cam ④ increases.

The hair hygrometer is designed so that the two special cams cause the movement of the pen arm to be proportional to the change in humidity. The hair hygrometer uses a recording chart with a humidity scale divided into 100 equal segments. Each segment corresponds to 1%. So, humidity can be directly read from the recording chart.

(2) Precautions for using the hair hygrograph

1) Before taking a reading of the hair hygrograph, gently tap the hygrometer to remove any mechanical tension added to the hair bundle.
2) At every measurement with the hair hygrograph, the reading should be compared with the humidity measured with the aspirated psychrometer at the same time. The difference of the humidity between them is used as a correction value.
3) Time marks as well as the degree of clock accuracy should be recorded on the chart.

<Notes>

a) When making a time mark on the recording chart by moving the pen, take care to move the pen arm downward. Moving the pen arm in the pen arm in the opposite direction(upward)makes the hair bundle to expand, causing the hygrograph to become defective.
b) To determine the humidity from the recording chart, read the indication on the record then correct it with correction values obtained by the procedure above.

(3) Sources to cause errors

a) Hair expands or shrinks due to changes in temperature as well as those in humidity. The expansion or shrinkage of a hair corresponding to a temperature change of 1℃ is about 1/15 of the expansion or shrinkage of a hair corresponding to a temperature change of 1% in usual air temperatures. Thus no special temperature compensation is made in hair hygrograph. However, if the temperature varies considerably, slight errors will occur. Because the hygroscopicity of hair begins to decrease at around -15℃ and becomes almost nil at -40℃, the hair hygrometer does not serve at extremely low air temperatures.
b) The response of hair to humidity has hysteresis. The hair length changes more when humidity increases than when it decreases. The change of hair length observed when humidity increases is up to 5 to 6% larger than that observed when humidity decreases.

c) The response time of the hair hygrometer depends on air temperature. The time constant of the hair hygrometer, is about 10 seconds at 20℃ and about 30 seconds at -30℃.

d) After the hair hygrometer is exposed in low temperature and low humidity for a long time , reading error increase due to the increasing of delay. This state could not be recovered until the hair is saturated.

e) Hair is highly sensitive to contamination such as dust, ammonia, oil which adheres to hair when a finger directly touches it, and exhaust gas.

f) Moving the pen arm to her direction the hair is tensioned makes the hair elongate and causes a malfunction of the hair hygrometer.

g) If a hair hygrometer is left in the low humidity condition for a long time, its reading changes causing large errors.

h) If the difference in reading between a hair hygrometer and an aspirated psychrometer is 5% or more on average over 10 days, the hair hygrometer should be considered faulty.

(4) Maintenance

Routine maintenance

a) Clean the dusty hair bundle with dust or smoke with a soft brush.

b) If the hair bundle is extremely dirty or it has been used for several months, clean it with a painting brush soaked with distilled warm water by gently touching the bundle.

c) Do not touch the hair bundle directly. Each of the parts of the hair hygrometer operates under slight forces. When cleaning the parts, be sure to treat them gently

Periodic maintenance

a) Clean the hair bundle with a feather brush, wash it with a painting brush.

b) Make offset adjustments by comparing the reading of the hair hygrometer with that of the aspirated psychrometer.

(5) Calibration

A hair hygrograph is calibrated by comparison with a working standard hygrometer in a humidity generator chamber. Keep in mind that the response times of the hair hygrograph and the working standard hygrometer are different. It is necessary that the temperature and humidity are kept constant in the chamber during the comparison. The aspirated psychrometer is the simplest and the most correct working standard hygrometer.

Even if no humidity generator is available, it is possible to make calibration by wetting the hair bundle with water to reach the humidity of 100%. Note that if a hair bundle is soaked with too much water, offset adjustments cannot be made correctly. The humidity in the room will be measured for calibration of the lower humidity condition. The difference between a hair hygrograph and a working standard hygrometer is analyzed from three or more data. The long-term stability and checked by comparisons for a prolonged period.

(6) Repair

a) The pivots and pillows have been heat treated. If these parts are corroded, they should be ground with an oil grind stone ensuring that they are not eccentric.

b) If ink is deposited on the pen, remove the pen from the pen arm, wipe off the ink, and clean the pen in alcohol.

c) If a ink channel is clogged and ink does not flow regularly, insert a piece of thin paper through the slit liquid.

d) If the contact points of the cams becomes dirty, polish it with a cloth moistened with metal polish liquid.

e) Do not touch the lever because adjusting the lever of the hair hygrometer causes the change in its magnification. Clean the other parts regularly.

(7) Transportation and installation

Transportation [See 1.5(3),"Transportation of instruments"

a) Tie the pen arm to the pen tip retainer loosely.

b) Tie the plumb attached to the main cam to the hinge of the pen arm.

c) Attach cardboard or a plate to the glass parts.

d) Insert paper between the central axis and the nuts pressing the clock-driver drum to eliminate the backlashes above and below the clock-driver drum.

e) Wrap the humidity sensor unit in wrapping paper.

f) Records of all calibration results should be put into the instrument.

g) Attach a label indicating the type of the instrument and the name of the observation site.

h) Wrap the whole instrument in wrapping paper. Place the instrument in a robust box with legs so that the instruments cannot be set incorrectly. Place packing around the instrument to avoid vibrations. Put the indication of "This Side Up" and "Handle with Care" on the box.

Installation[See 1.5 (4),"Siting and Exposure"]

a) The hair hygrometer should be installed in an thermometer shelter.

b) Do not install a hair hygrometer near animal sheds or factories using ammonia. As ammonia damages the hair.

c) In cold areas, set a well-ventilated cover over the hair hygrometer to protect it from snow or ice during sever conditions such as snowstorms.

d) Leave a hair hygrometer which has not been used for prolonged periods in an thermometer shelter for two or three days before the beginning of its use.

3.2.3 Electronic hygrometer (capacitive type)

(1) Structure and composition

Electronic hygrometers detect the change in the electrostatic capacity or electric resistance of a sensor when it absorbs moisture. In this section, the electrical capacitive hygrometer is described.

The electrical capacitive hygrometer uses a dielectric material made of high polymer membrane, as a sensor.

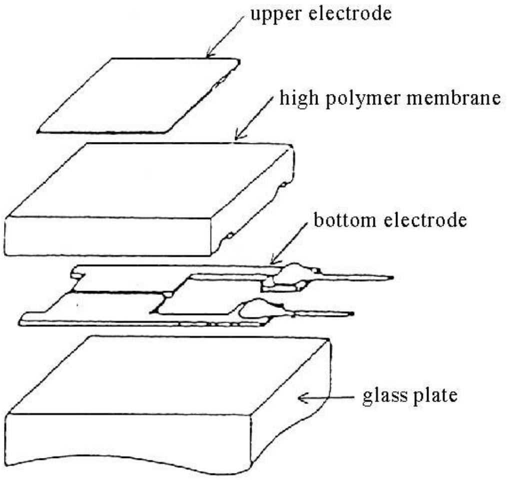


Figure 3.4 Structure of hygrometer sensor with high polymer membrane

Figure 3.4 shows the basic structure of the high polymer membrane humidity sensor, and Figure 3.5 shows the appearance of the electronic hygrometer used by the Japan Meteorological Agency.

The sensor is fitted with a filter which protects the sensor from contaminants, such as toxic gases, and has pores to tale moisture in it. Figure 3.6 shows an example of such a filter.

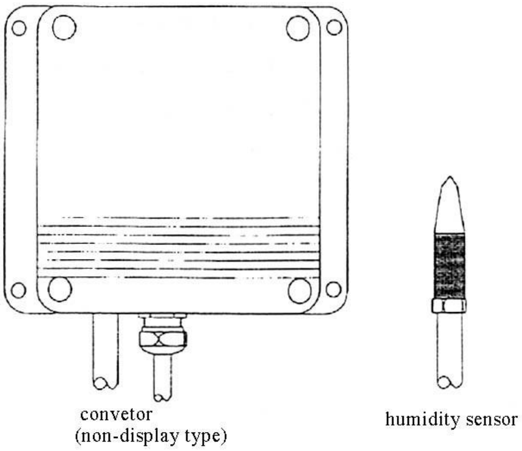


Figure 3.5 Outline of electrical hygrometer used in JMA

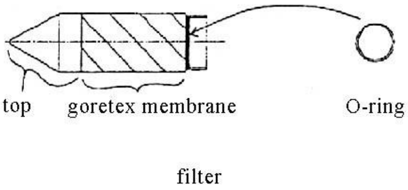


Figure 3.6 Outline of filter used in electrical hygrometer

(2) Characteristics of the sensor

The measurement range of the electrical capacitive hygrometer is from 0 to 100%, and its accuracy can be improved by calibration. By calibrating with the standard hygrometer, the electrical capacitive hygrometer attains the error of 1% or less in the range from 0 to 90% and error of 2% or less in the range from 90 to 100%.

The hysteresis becomes large when the humidity changes from high to low. It is within 1% at relative humidity of 60-80%.

when relative humidity increases from 0 to 90% and the sensor absorbs moisture, the time constant of the sensor is about six seconds. On the other hand, when relative humidity decreases from 90 to 0% and the sensor releases moisture, the time constant is about 10 seconds.

For meteorological purposes, the sensor is put in a ventilation shelter to protect the sensor from precipitation and sunlight with the aspiration speed of 2 to 4 m/s around the sensor. The time constant with the shelter from the saturation to the room humidity is about 20 minutes, which is longer than that without the shelter, because of the shelter's large thermal capacity.

A high polymer membrane humidity sensor has temperature dependence of about 0.1%/℃ for the temperature range from 5 to 30℃ and 0.2%/℃ for the temperature range from –30 to 0℃. Therefore, a temperature sensor is installed together with the humidity sensor to compensate its temperature dependency.

(3) Sources to cause errors

a) Any difference between the ambient temperature and the sensor temperature causes an error. For example, at 20℃ and 50%RH, a difference of 1℃ between the ambient temperature and the sensor temperature results in an error of about 3%. At 90%RH, the error becomes up to about 6%. When the sensor temperature is lower than the ambient temperature in a low humidity condition, dew may form on the surface of the sensor. This will make a large measurement error. The sensor is housed in an ventilation shelter to reduce or eliminate the difference of temperature between the sensor and the ambient air to prevent dew formation.

b) The electronic capacitive hygrometer can be used in any environment where the human can live. However, do not use the hygrometer in the atmosphere containing oil mist, flammable gas, dust, organic solvents, acid, alkaline or ammonia. Using the hygrometer in the atmosphere may cause its sensor electrodes to corrode, thus the sensor life is shortened. To prevent the sensor electrode from corrosion, a protection filter is used to keep out dust or organic solvents.

(4) Maintenance

Routine maintenance

Routine maintenance is not needed.

Periodic maintenance

a) Compare the electrical capacitive hygrometer with the aspirated psychrometer once three months to observe time-dependent changes.

b) Replace the protection filter with a new one twice a year. In rural areas where little soot is found , the interval between replacements may prolonged to a maximum of once a year.

(5) Calibration

If a humidity generator chamber is available, an electrical capacitive hygrometer is calibrated in the same way as the hair hygrometer.

The sensor of the electrical hygrometer can be separated from display and recording units. This enables the calibration in a small humidity generator chamber, in which it is easy to attain various humidity. Use aspirated phychrometer or chilled-mirror dewpoint hygrometer as standard instrument.

(6) Repair

Because most of parts of the humidity sensor cannot be repaired, they must be replaced with new ones if they become defective. Refer to the instruction manual of the hygrometer on the method to identify defects and to replace parts.

(7) Transportation and installation

[See 1.5(3), "Transportation of instruments" and 1.5(4), "Siting and Exposure"]

Ask the manufacturer of the hygrometer for information about transportation, because precautions for transportation differ by the type of the hygrometer.

The method of installation of the hygrometer sensor is basically the same as that of the aspirated psychrometer.

3.2.4 Chilled-mirror dewpoint hygrometer

(1) Structure and composition sensor (mirror)

The basic structure of the sensor unit for a chilled-mirror dewpoint hygrometer is shown in Figure 3.7. Sample air is drawn to the metallic mirror surface through piping to determine the dewpoint temperature. As the mirror cools, condensation forms when its surface temperature falls below the dewpoint temperature, but evaporates and disappears at higher temperatures. The temperature of the metallic mirror when condensation forms is measured using a platinum resistance thermometer, and the result is taken as the dewpoint temperature. Condensation conditions are monitored using a photo-detector with the reflection of a light-emitting diode (LED) on the mirror. Irradiated light is scattered when condensation is present, and the amount of reflected light changes with the mirror's surface condition. A peltier element is used to control the mirror's temperature..

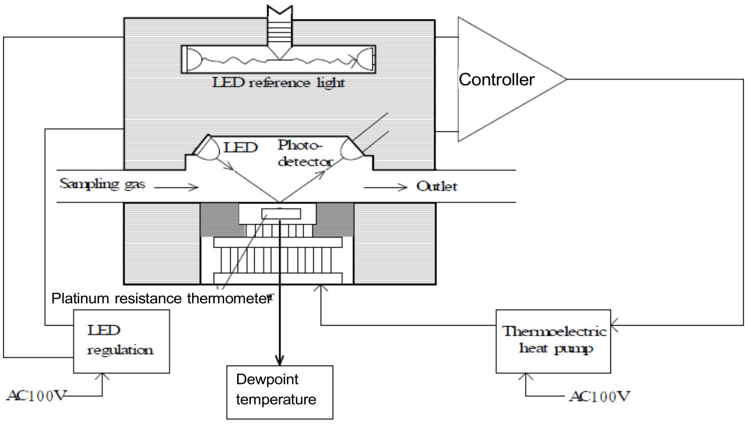


Figure 3. 7 Structure of a chilled-mirror sensor unit

(2) Structure

Chilled-mirror dewpoint hygrometers consist of a sensor unit with a mirror, an indicator to output the measurement results, and a pump to draw sample air into the sensor unit. The sample flow can be adjusted using the pump, and a filter should be installed if the sample air has a high contaminant content (Figure 3.8).

With models to which a thermometer can be attached to measure the temperature of the sample air, relative humidity can be calculated based on the sample temperature and the dewpoint temperature.

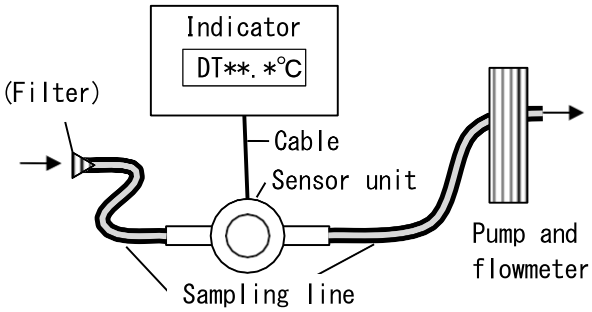


Figure 3.8 Structure

(3) Error factor

Contaminants such as salt, dust and oil mist on the mirror may result in artificially elevated dewpoint temperature readings or difficulties in stable condensation layer formation due to temperature control malfunction. As absorbent piping will draw vapor from the sample and create large errors, it is important to use stainless steel or fluoride-based resin pipes and to make them as short as possible.

(4) Maintenance

As mirror contamination can cause errors, the mirror should be cleaned with a special detergent before measurement. Leaving the unit on high temperature after measurement can also result in the development of mold or corrosion. After measurement ends, the hygrometer should be dried completely by blowing dry air through it.

(5) Calibration

If a humidity generator tank is attached, calibration should be conducted by connecting piping in parallel from the tank to both the instrument to be calibrated and the standard instrument, measuring the dewpoints at the same time and comparing them. Thermometers should also be calibrated when relative humidity is to be determined.

(6) Repair

Severely corroded mirrors cannot be repaired and must be replaced. As the procedures for identifying faults, replacing units and conducting similar work depend on the model, the instruction manual should be followed.

(7) Transportation and installation

(See 1.5 (3) Transportation of instruments and 1.5 (4) Location and method of installation)

3.3 Example of calibration

(1) Chilled-mirror dewpoint hygrometer measurement and calibration

An example involving a traveling standard chilled-mirror dewpoint hygrometer (Picture 3.1) is outlined below.

Picture3.1 Traveling standard instrument

(2) Preparation

The conditions of the sensor unit, indicator, suction pump, piping, cables and special cleaning tools should be checked. If data are to be recorded using a PC, an RS232C cable to connect the indicator and the PC is required. A connection diagram is shown in Figure 3.9.

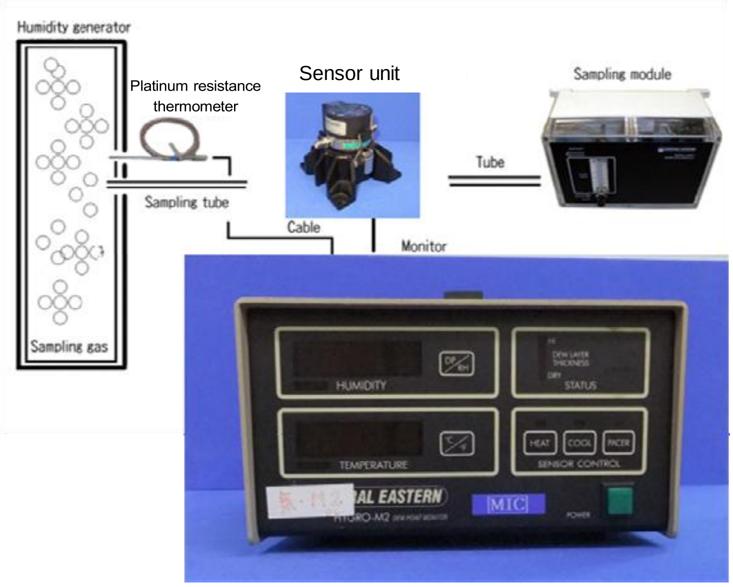


Figure 3.9 Connection diagram

(3) Measurement

i. Check that the filter on the electric hygrometer to be calibrated is clean.

ii. Clean the mirror of the traveling standard unit using the proper tools.

iii. Set up the traveling standard sensor, the thermometer to measure the sample-air temperature and the sensor of the instrument to be calibrated inside a hygrometer calibration chamber. Place all the sensors as close as possible to the center of the chamber (Figure 3.10).

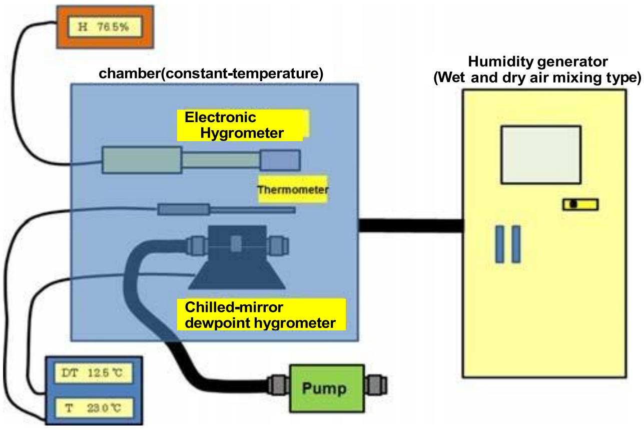


Figure 3.10 Connection diagram (at calibration)

iv. Connect the sensors inside the chamber and the indicators outside it. For standard instruments (chilled-mirror dewpoint hygrometers), connect the sensor to a suction pump outside the chamber and adjust the flow to the standard value of 0.7 [L/min] using the knob on the pump. Check the flow using the flow meter attached to the pump.

v. If digital data can be output from the converter of the instrument to be calibrated, connect it to a PC and record the data.

vi. Operate the thermo-hygrostat test chamber as detailed in the operation manual.

vii. Measure the room temperature to ensure it is within the operational range and record it. For details of the operational temperature range, consult the instrument owner or refer to the operation manual of the instrument to be calibrated.

viii. Check the stability of the sample temperature (the standard deviation should be 0.01°C or less).

ix. Check the stability of the dewpoint temperature (the standard deviation should be 0.01°C or less).

x. Repeat calibration using the method described in Paragraph 2. Environmental conditions must be measured at the beginning, in the middle and at the end of calibration for each day.

xi. Measurement must be performed several times back and forth from low to high humidity and from high to low humidity.

The average calculated from the measurement data (i.e., the difference between the humidity of the reference standard and that of the instrument to be calibrated) is the calibration result.

xii. Once calibration is complete, shut off the power to the hygrometer and dry it completely by letting low-humidity air (or dry air) flow into its sensor unit.

Chapter 5: Measurement of Surface Wind

CONTENTS

Chapter 5: Measurement of Surface Wind

4.1 Definitions and Units

Natural wind in the open air is a three-dimensional vector that has the directions of north, south, east and west in addition to vertical components and magnitude (i.e., wind speed). As the vertical component is ignored for most operational meteorological purposes, surface wind is practically considered as a two-dimensional vector.

Wind blowing over the earth’s surface is turbulent, and is characterized by random fluctuations of speed and direction. This can be seen in smoke drifting from a chimney, for example, as it fluctuates from quick to slow and backward, right, left, up and down. This rapid fluctuation is called gusting.

Wind speed is classified into instantaneous and average types. The average wind speed is the average of the instantaneous wind speed over a ten-minute period. As described above, however, wind speed fluctuates continuously, and measured values of instantaneous wind speed are affected by anemometer response characteristics. Defined below are some basic terms and units used in wind measurement, with a focus on those related to response characteristics that affect anemometer performance.

4.1.1 Definitions

1) **Wind passage (L (m))**: The distance that wind (air mass) covers over a given period of time (t).

2) **Instantaneous wind speed (V_i (m/s))**: Wind speeds change very quickly, and the numerical expression for instantaneous wind speed (V_i) at time (t) is expressed as follows:

$$Vi = \lim_{\Delta t \to 0} \frac{\Delta L}{\Delta t} = \frac{dL}{dt}$$

where ΔL is the distance the wind travels from one time (t) to another (t +Δt) (m) and Δt is the short period since the initial time (t) (s). The maximum instantaneous wind speed (peak gust) is the maximum observed instantaneous wind speed over a specified period of time.

3) **Average wind speed (V_m (m/s))**: The numerical expression for the average wind speed (V_m) at time (t), in m/s, is defined as follows:

$$V_m = \int_{t_0}^{t_0+t} V_i \frac{dt}{t} = \frac{L}{t}$$

where L is the distance the wind travels from one time (t_0) to another (t_0 + t) (m), Vi is the instantaneous wind speed (m/s), and t is the measurement period since the initial time (t_0) (s).

4) **Starting threshold speed (V_0 (m/s)):** The lowest wind speed at which a rotating anemometer mounted in its normal position starts to turn continuously.

5) **Response length (L_d (m)):** The distance that an air mass moving through a rotating

anemometer travels in a given time period (time constant) required for the output of an anemometer's sensor to reach 63% of the equilibrium wind speed after a step change. The numerical expression for the response length L_d is defined as follows:

$$L_d = V \times \tau \text{ (m)}$$

where V is the final indicated wind speed and τ is the constant of the instrument.

6) **<u>Critical damping</u>:** The damping actuated when the direction of a wind vane changed stepwise reaches equilibrium with the fastest transient response without overshoot.

7) **<u>Overshoot (θ)</u>:** The amplitude of a wind vane's deflection when it oscillates after release from the initial displacement.

8) **<u>Overshoot ratio (Ω)</u>:** The ratio of two successive overshoots as expressed by the following equation:

$$\Omega = \theta_{(n+1)} / \theta_n$$

where θ_n.and. $\theta_{(n+1)}$ are the nth and n + 1th overshoots, respectively.

In practice, since deflections after the first overshoot are usually small, the overshoot ratio is determined by the deflection of the initial release point (n = 0) and the first deflection after release (n = 1)(Figure 4.1).

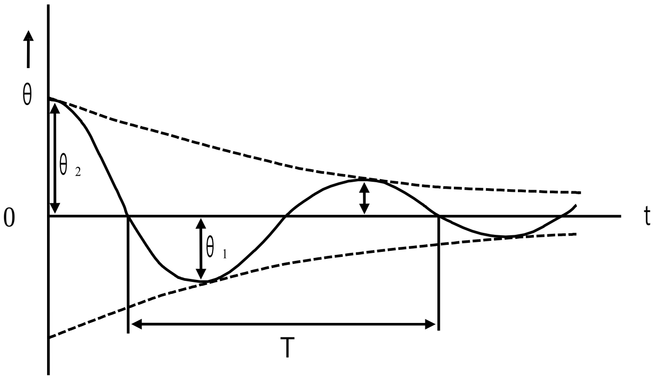


Figure 4.1 Overshoot of damping oscillation

9) **<u>Damping ratio (ξ)</u>:** The ratio of actual damping to critical damping as expressed by the following equation:

$$\xi = \left(\frac{1n(1/\Omega)}{\left[\pi^2 + [1n(1/\Omega)]^2\right]^{1/2}} \right)$$

where Ω.is the overshoot ratio.

WMO recommends a damping ratio in the range of 0.3 to 0.7. Figure 4.2 shows wind vane response according toξ..

If ξ.< 1, underdamping occurs, and if ξ.= 0, single harmonic motion with no resistance at all is seen.

If. ξ.= 1, critical damping occurs.

If. ξ.> 1, the wind vane does not oscillate; the time until equilibrium is long, and it is sometimes unclear whether equilibrium has been reached. This is called overdamping.

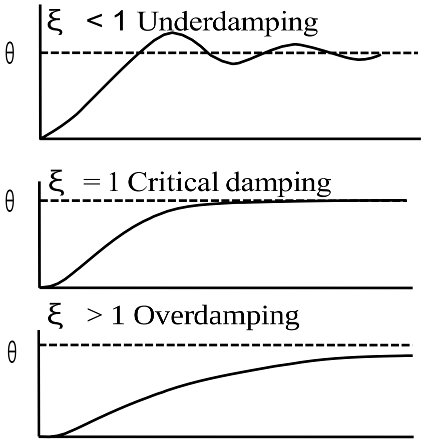


Figure 4.2 Oscillation changes by damping ratio

4.1.2 Units

A number of different units are used to indicate wind speed, including meters per second (m/s), kilometers per hour (km/h), miles per hour (mph), feet per second (ft/s) and knots (kt). In synoptic reports, the average wind speed measured over a period of 10 minutes is reported every 0.5 meters per second (m/s) or in knots (kt). Table 4.1 shows the conversion for these units.

Table 4.1 Speed conversion table

kt	m/s	km/h	mph	ft/s
1.000	0.515	1.853	1.152	1.689
1.943	1.000	3.600	2.237	3.281
0.868	0.447	1.609	1.000	1.467
0.540	0.278	1.000	0.621	0.911
0.592	0.305	1.097	0.682	1.000

Wind is described in terms of the direction from which it blows, and is given as compass-point expressions graduated into 8 or 16 directions clockwise from true north (Figure 4.3).

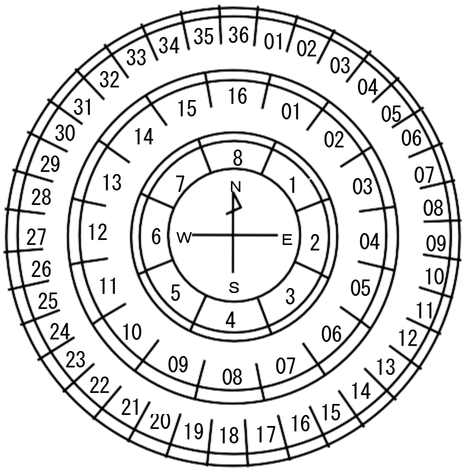


Figure 4.3 Wind-direction scale

In synoptic reports, the average wind direction over 10 minutes is reported in the same way as for wind speed in degrees to the nearest 10 degrees using a code number from 01 to 36. By way of example, 02 means that the wind direction is between 15° and 25°. Wind with an average speed of less than 1 kt is termed calm, and its direction and speed are both reported as “00.”

4.2 Principles of Measuring Instruments

Surface wind is usually measured using a wind vane and a cup or propeller anemometer.

When a measuring instrument malfunctions, or when no such instrument is available, the wind direction and speed may be estimated subjectively.

This section mainly describes the principles of measurement using vanes and rotating anemometers (cup and propeller types) and the response characteristics of these instruments.

4.2.1 Wind Estimation

If a measuring instrument becomes faulty or is not available, wind can be estimated by visual means such as observing smoke as a guide to wind speed and using the Beaufort Scale(Table 4.2).

It is also possible to estimate wind direction by observing the flow of smoke or the movement of a flag. Streamers at airports can also be used when the wind speed is high enough.

When wind is monitored visually, the following points should be noted:

* Stand directly under the indicator to eliminate any perspective-related errors.

* Do not mistake local eddies resulting from the surrounding conditions (buildings, for example) for the general wind direction.

* Do not use the direction of cloud movement as an indicator even if their altitude seems low.

Table 4.2 Beaufort Scale

Beaufort Scale number and description	Wind speed equivalent at a standard height of 10 meters above open flat ground				Specifications for estimating speed over land
	(kt)	(m/s)	(km/h)	(mph)	
0 Calm	< 1	0 – 0.2	< 1	< 1	Calm; smoke rises vertically.
1 Light air	1 – 3	0.3 – 1.5	1 – 5	1 – 3	Direction of wind shown by smoke-drift but not by wind vanes.
2 Light breeze	4 – 6	1.6 – 3.3	6 – 11	4 – 7	Wind felt on face; leaves rustle; ordinary vanes moved by wind.
3 Gentle breeze	7 – 10	3.4 – 5.4	12 – 19	8 – 12	Leaves and small twigs in constant motion; wind extends light flags.
4 Moderate breeze	11 – 16	5.5 – 7.9	20 – 28	13 – 18	Raises dust and loose paper; small branches are moved.
5 Fresh breeze	17 – 21	8.0 – 10.7	29 – 38	19 – 24	Small trees in leaf begin to sway, crested wavelets form on inland waters.
6 Strong breeze	22 – 27	10.8 – 13.8	39 – 49	25 – 31	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty.
7 Near gale	28 – 33	13.9 – 17.1	50 – 61	32 – 38	Whole trees in motion; inconvenience felt when walking against the wind.
8 Gale	34 – 40	17.2 – 20.7	62 – 74	39 – 46	Breaks twigs off trees; generally impedes progress.
9 Strong gale	41 – 47	20.8 – 24.4	75 – 88	47 – 54	Slight structural damage occurs (chimney-ports and slates removed).
10 Storm	48 – 55	24.5 – 28.4	89 – 102	55 – 63	Seldom experienced inland; trees uprooted; considerable structural damage occurs.
11 Violent storm	56 – 63	28.5 – 32.6	103 – 117	64 – 72	Very rarely experienced; accompanied by widespread damage.
12 Hurricane	64 and over	32.7 and over	118 and over	73 and over	-

4.2.2 Vanes

Vanes are classified into wind vane and aero vane types. Wind vanes are used alone, while aero vanes are used with a propeller anemometer and a wind direction plate, which looks like the vertical tail part of an airplane.

4.2.2.1 Wind Vanes

A one-vane weathercock is the most basic wind vane; various types of vanes have been developed, as shown in Figure 4.4.

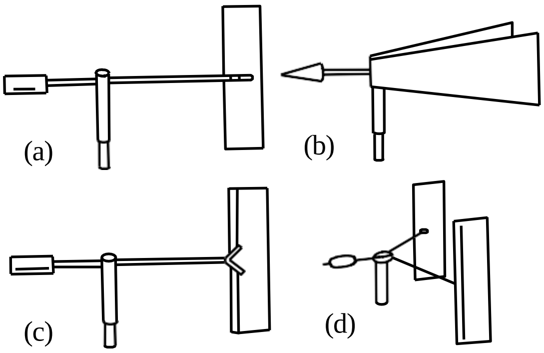


Figure 4.4 Types of wind vane

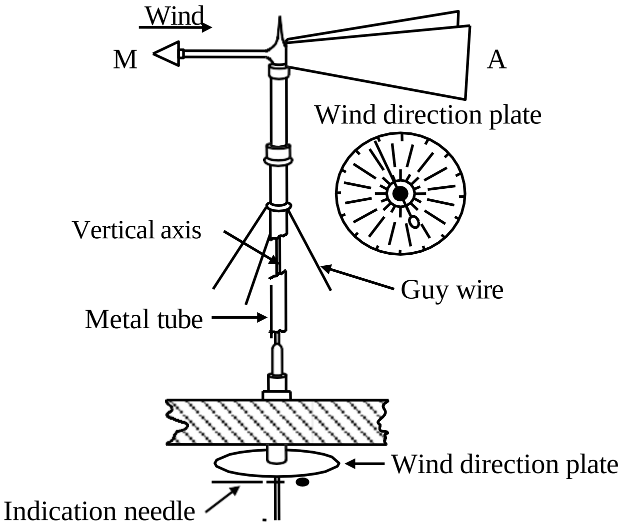


Figure 4.5 Wind vane

In the case of wind vane (b) shown in Figure 4.4, the Y-shaped vane shown in Figure 4.5 is fitted in such a way that the two metal plates A are positioned to form an angle of about 20 degrees. A weight, M, is attached to the top of the vane for balance. A steel pipe passes through the top and is attached to the roof, and the axis is fitted through the steel. To indicate the rotation angle of the vane, a compass is directly mounted on the rotation axis. To enable remote indication of the vane's angle of rotation, a potentiometer or selsyn motor is mounted on the rotation axis.

4.2.2.2 Wind Direction Signal Converters

A wind direction transmitter is a device used to convert the angle of the wind direction axis into an electrical signal. Equipment including a potentiometer, a selsyn motor and an encoder system is used for this purpose. This section describes the principles of vanes using these converters.

[Principles of Vanes with a Potentiometer]

A vane with a potentiometer is designed to generate a voltage proportional to the change in the angle of the potentiometer's sliding contactor mounted in the wind direction.

Figure 4.6 shows a ring potentiometer, which consists of a transmitter and a receiver. The transmitter has three taps, and the receiver consists of a rotor encompassing a permanent magnet and a stator with three 120° coil windings. This rotor has a pointer that indicates the wind direction.

A 12-volt direct voltage is fed to the potentiometer through a sliding contactor that has a pair of contact points directly coupled to the wind direction axis. A current from the position of the sliding contactor (slide rheostats) is applied to the three coils of the stator in the receiver through the three taps of the potentiometer that generates the magnetic field of the stator. A pointer fastened to the rotor indicates the angle proportional to the sliding-contactor position, namely the wind direction.

The three taps of the potentiometer are usually connected to the receiver with cables to enable observation of the wind direction from remote locations.

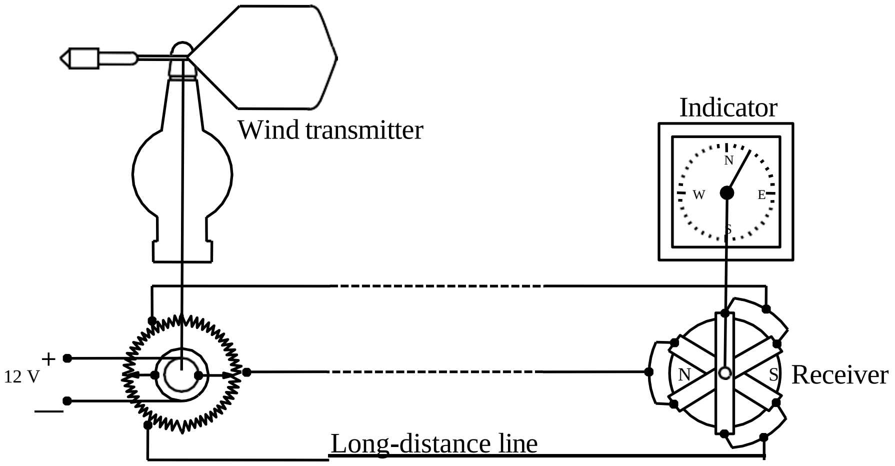


Figure 4.6 Ring-potentiometer assembly

The advantages of this type of indicator are that it is simply designed and can be installed easily as a signal converter. Its disadvantages are that the sliding contactors wear quite rapidly and that the torque of the receiver to move the indicator pointer is small. In addition, the electrical resistance of the cables between the potentiometer and the receiver is greatly affected by the distance between the vane and the indicating device. Large wind-direction errors may also appear if the connection of the three cable leads is not tight.

[Principles of Vanes with a Selsyn Motor System]

These vanes have two selsyn (self-synchronous) motors with the same structure – one mounted on the vane (the transmitter) and the other on an indicating device (the receiver). Torque generated in the motor on the vane in response to changes in the vane's angle of rotation is electrically transmitted to the recorder or indicator so that the wind direction can be ascertained.

Selsyn motors are used to electrically transmit the angle of rotation of the transmitter's axis to the receiver so that the angle of rotation of the receiver's axis can be made to match it. A selsyn motor consists of a stator with three windings set 120 degrees apart and a rotor with a bi-polar winding.

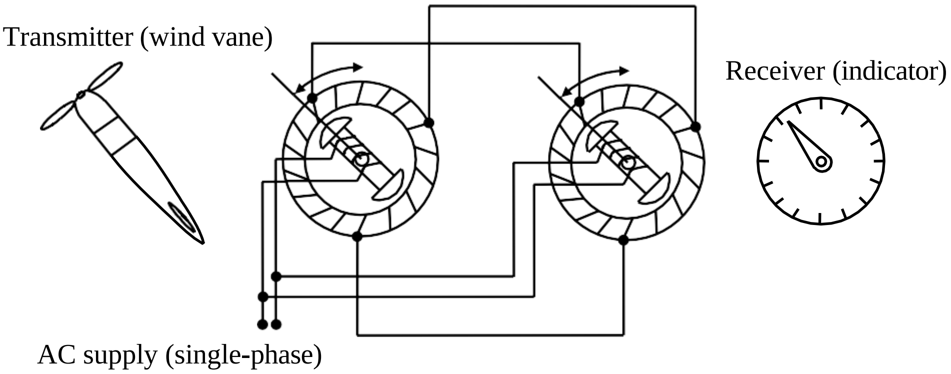


Figure 4.7 Selsyn motor

One selsyn motor is connected to the other as shown in Figure 4.7. If the position of the transmitter’s rotor does not correspond to that of the receiver, the voltage induced in each of the transmitter’s three windings does not correspond to that in each of the receiver’s three windings. A current consequently flows that generates torque to make the receiver’s angle follow the transmitter’s rotation. The same torque also acts on the transmitter, but the transmitter is restrained by wind pressure. Consequently, the axis of the receiver, which has a very light pointer, rotates until its angle corresponds to that of the transmitter.

The selsyn system is capable of synchronizing the rotation angle of one selsyn motor with that of the other.

[Principles of Vanes with an Optical Pulse Encoder]

As shown in Figure 4.8, an optical pulse encoder consists of a disk featuring a special pattern of concentrically cut slits with light-emitting diodes (light transmitters) and phototransistors (light receivers).

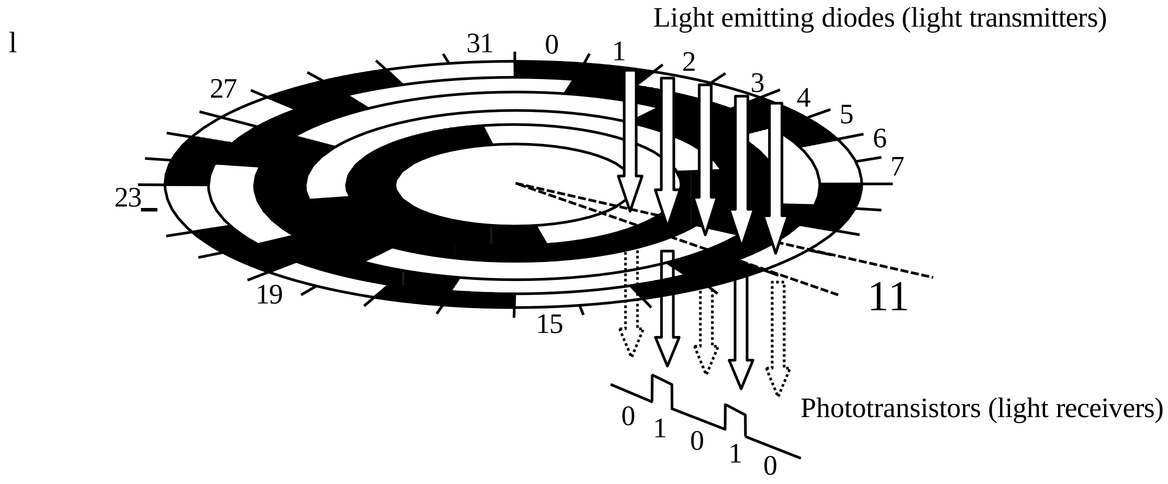


Figure 4.8 Digital angle-encoder disk (5-bit)

The pulse encoder used with the vane is designed to have a specific number of bits that meets the required angle resolution. If the angle is represented with five or eight bits, its resolution is as follows:

$$360° \div 2^5 = 360 / 32 = 11.25°$$
$$360° \div 2^8 = 360 / 256 = 1.4°$$

If a beam of light from a light transmitter passes through the circular disk and reaches the light receiver, a signal of “1” is output. If the beam is reflected by the disk and does not reach the receiver, a signal of “0” is output. The principle of wind direction measurement with a five-bit encoder is shown in Figure 4.8. When the beams of light pass through the disk in the manner shown, a signal of 01010 is generated. The 11th segment shown in the figure corresponds to an angle between 11th ×11.25° and 12th ×11.25°, namely between 123.75° and 135.00°.

Optical pulse encoders have two advantages: they are free of mechanical friction because they have no contacting parts, and superior response characteristics can be achieved by making the unit small and lightweight. In addition, they are suitable for data processing with a computer because the output can be processed as digital signals.

4.2.2.3 Vane Response Characteristics

Propeller anemometers and wind vanes cannot respond to rapid changes in wind direction. Delayed response to such changes significantly affects errors in wind speed observation, especially with propeller anemometers.

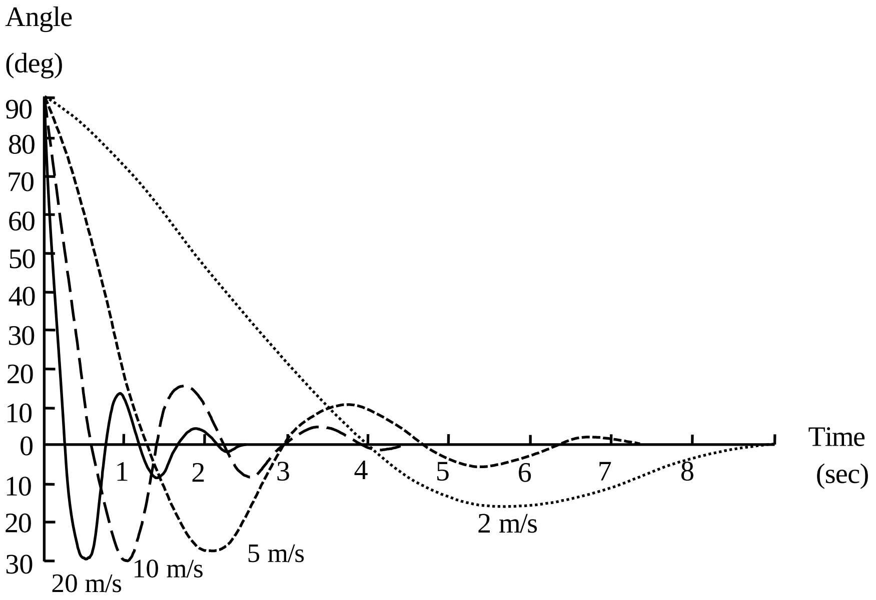


Figure 4.9 Wind-vane response characteristics

Figure 4.9 shows the response characteristics of a propeller anemometer upon exposure to wind speeds of 2, 5, 10 and 20 m/s in a wind tunnel when the propeller axis is oriented at 90° away from the air flow at a constant speed and released. The way it gradually changed direction with oscillation and faced the wind flow directly was observed. As is apparent from the figure, the higher the wind speed, the more quickly the propeller axis faced the airflow directly.

If the wind direction changes within the time the propeller axis takes to face the wind direction directly, the response will be delayed and wind speed cannot be measured accurately. A high-performance propeller anemometer should reduce its amplitude quickly and have a short oscillation period.

4.2.3 Rotating Anemometers

There are two types of rotating anemometer: the cup anemometer, which has three or four cup wheels attached to the rotating axis, and the propeller anemometer, which has propeller blades. Both types rely on the principle that the revolution speed of the cup or propeller rotor is proportional to the wind speed.

Rotating anemometers can be classified as the generator type or the pulse generator type according to the type of signal generator used. The generator type is a kind of wind power generator whose cup or propeller axis is directly coupled to the axis of a generator that generates voltage from their rotation. As the generated voltage is proportional to the revolution speed of the cup or propeller rotor and thus to the wind speed, the wind speed can be measured. The two types of generator are the AC (alternating current) and the DC (direct current) kinds. As a DC generator requires a commutator (i.e., a collector and brushes) and has a more complicated structure than an AC generator, the AC generator type is widely used.

Rotating anemometers with a pulse generator come in several different types, including one that generates electrical pulse signals using an electrical contact-breaker and one that generates optical pulses using an optical light-chopper converter. The latter consists of a light-emitting diode, a perforated disk fixed to the axis of the rotation sensor and a phototransistor. The number of pulses, which is proportional to the number of anemometer revolutions (and thus to the wind speed) is counted to ascertain the wind speed.

These anemometers measure instantaneous wind speed. The average wind speed is obtained using either the pulse-of-wind-passage method or with a CR integrated circuit (a combination of capacitors and resistors), or alternatively with a microprocessor. These measurement principles are explained in the following sections.

4.2.3.1 Cup Anemometers

A cup anemometer has three or four cups mounted symmetrically around a freewheeling vertical axis. The difference in the wind pressure between the concave side and the convex side of the cup causes it to turn in the direction from the convex side to the concave side of next cup. The revolution speed is proportional to the wind speed irrespective of wind direction. Wind speed signals are generated with either a generator or a pulse generator.

A cup anemometer has three or four cups mounted symmetrically around a freewheeling vertical axis. The difference in the wind pressure between the concave side and the convex side of the cup causes it to turn in the direction from the convex side to the concave side of next cup. The revolution speed is proportional to the wind speed irrespective of wind direction. Wind speed signals are generated with either a generator or a pulse generator.

The cups were conventionally made of brass for its qualities of rigidity and rust resistance. In recent years, however, cups made of light alloy or carbon fiber thermo-plastic have become the mainstream, allowing significant reductions in weight. Beads are set at the edges of the cups to add rigidity and deformation resistance. They also help the cup to avoid the effects of turbulence, allowing the stable measurement of a wide range of wind speeds.

[Principles of Wind Speed Measurement]

1) Generator-type Cup Anemometers

This type has a small AC generator coupled to its axis. The wind turns the cups and the generator to generate a voltage proportional to the instantaneous wind speed, and the signal is transmitted to the indicator(Figure 4.10). The CR integrated circuit calculates the average wind speed as the circuit charges and discharges the capacitor over a certain period. This type of anemometer is located in an exposed position on a tower and is connected to an indicator through cables, and observation from remote locations is possible. The greatest distance between the anemometer and the indicator depends on the electrical resistance of the cable and the design (a model allows a maximum distance of 1,500 m). This type of anemometer does not require a power supply for the main unit, but the counter takes 3-volt dry-cell batteries (Figure 4.11).

Recent models are equipped with an A/D (analog to digital) converter to allow computer processing of data tasks.

The generator-type cup anemometer generates wind speed signals by itself, and can be used without an electrical supply.

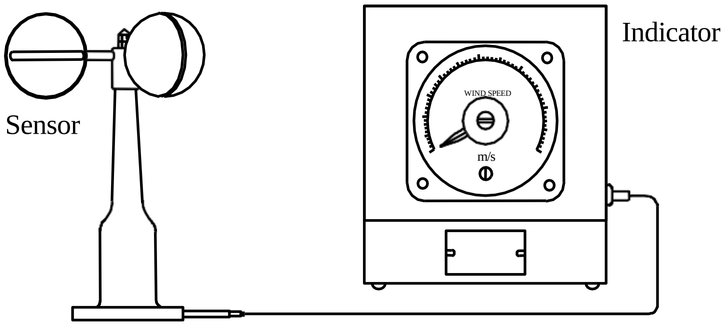


Figure 4.10 Generator-type cup anemometer

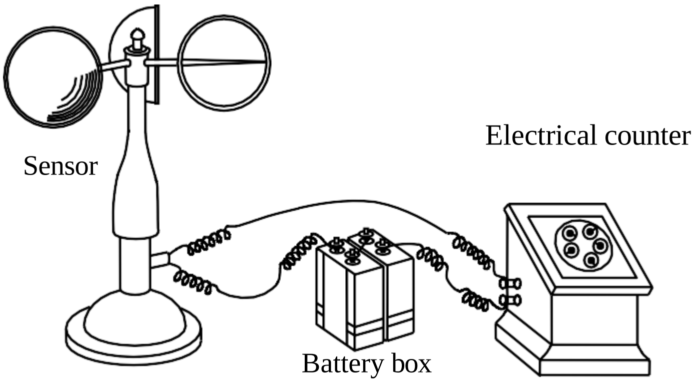


Figure 4.11 Connection of lead cables

2) Pulse Generator-type Cup Anemometers

A pulse generator-type cup anemometer counts the number of cup-wheel rotations, which is proportional to the wind passage. The number of rotations in a particular period (such as ten minutes) is counted, and the wind passage is obtained by multiplying the factor specified for the anemometer (e.g., 54 rotations for a wind passage of 100 m) by this number. The wind speed is obtained by dividing the wind passage by the number of time units in this period.

The optical pulse generator type is mainly used now, having replaced the electrical contact breaker type. An optical pulse generator consists of a perforated disk (called a chopper disk) directly fixed to the rotating axis of the cup wheel and a photocoupler. As the cup wheel rotates, the chopper disk turns and either allows the passage of or interrupts a beam of light between the light transmitter and the light receiver of the photocoupler, creating pulse signals with a frequency proportional to wind speed. After P/A (pulse-analog) conversion, a DC voltage proportional to the number of pulses in a specific period is generated. This voltage is then converted to give an instantaneous wind speed. Some cup anemometers with a pulse generator digitize signals and indicate the instantaneous wind speed with a microprocessor.

A CR integrated circuit or a microprocessor are used to obtain the average wind speed. For details of these methods, refer to the next section regarding pulse generator-type propellers.

The chopper disk and photocoupler of a pulse generator-type cup anemometer can be made small. The weight of a pulse generator-type cup anemometer can be less than that of the generator in a generator-type cup anemometer, allowing improved starting threshold speed and response characteristics.

3) Mechanical-type Cup Anemometers

A much simpler method for measurement of wind speed using a cup anemometer is to count the number of cup revolutions. A mechanical-type cup anemometer indicates the number of cup rotations through gears connected to the sensor axis. Specifically, the increment (wind passage) of indication over a period of ten minutes before the observation is read and the average wind speed are obtained by dividing the wind passage by 10 minutes (600 seconds) (Figure 4.12).

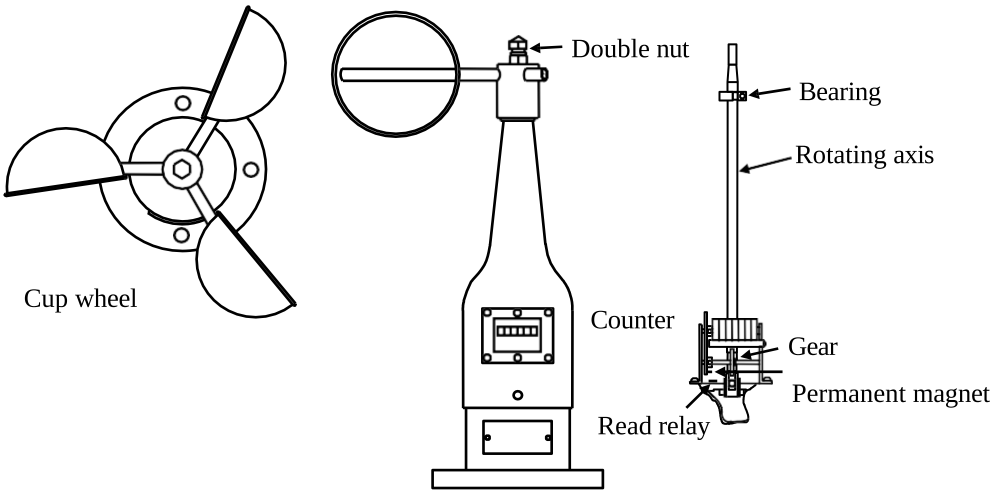


Figure 4.12 Three-cup-wheel wind-path anemometer

This type of anemometer has a number of advantages: it does not require a power supply, its structure is simple, and it remains relatively problem-free. However, its body is connected to the counter, and it is necessary to go outdoors to read the counter for each instance of observation. A type of anemometer with a reed-relay directly connected to the counter is available to eliminate the need to go outside to obtain readings, as the generated contact signals are counted with an electric counter indoors. In such cases, a DC 3V power supply is required for the electric counter.

4.2.3.2 Propeller Anemometers

A propeller anemometer has a sensor with a streamlined body and a vertical tail to detect wind direction and a sensor in the form of a propeller to measure wind speed integrated into a single structure. It measures wind direction and wind speed, and can indicate/record the instantaneous wind direction and wind speed in remote locations. It also measures the average wind speed using wind-passage contacts or by calculating the number of optical pulses. This type is used as the standard anemometer of the Japan Meteorological Agency (JMA).

There are generator-type and optical pulse generator-type propeller anemometers. At present, the optical pulse generator type is mainly used because its contact resistance is small over a wide range of wind speeds from weak to strong, and its measurement system can be made small and lightweight. Some anemometers are capable of measuring wind speeds from 0.4 to 90 m/s.

[Principles of Wind Speed Measurement]

1) Generator-type Propeller Anemometers

Figure 4.13 shows the main part of a generator-type propeller anemometer's transmitter sensor. It includes a propeller that reacts to wind pressure and turns at a rate corresponding to the wind speed, an AC generator, a tail assembly and a selsyn motor to generate wind direction signals.

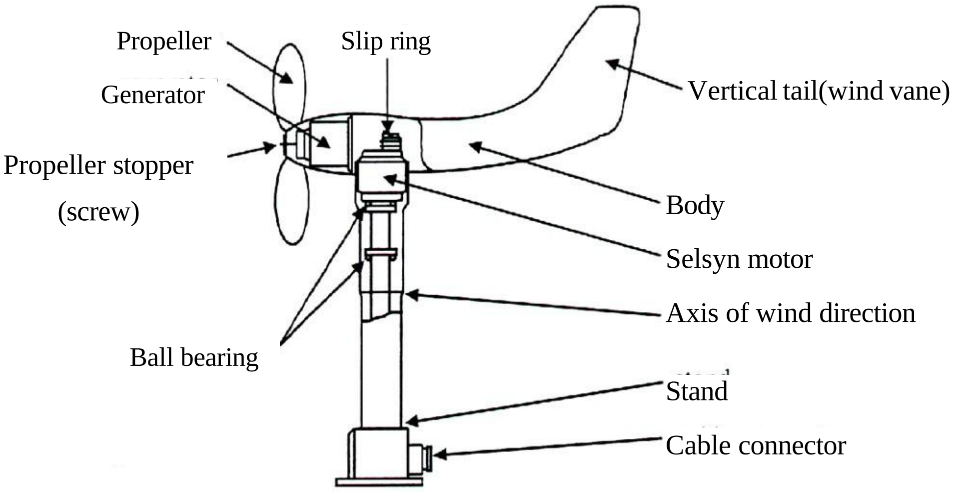


Figure 4.13 Generator-type propeller anemometer

To detect the wind direction and measure the wind speed accurately, the tail assembly of a propeller anemometer is designed so that the propeller always faces the wind. An AC generator connected to the propeller shaft generates induced voltages proportional to the wind speed. As shown in Figure 4.14, these AC voltage signals are rectified to a DC voltage and output as an analogue voltage signal proportional to the wind speed. The analogue voltage signal is transmitted to a wind speed indicator or a recorder in which a voltmeter is assembled, and the instantaneous wind speed is ascertained.

There is another type of propeller anemometer that uses a different method. As the propeller shaft undergoes a certain number of revolutions for a wind passage of 60 m or 100 m, for example, worm gears (i.e., a gear-reducing mechanism) coupled to the axis of the generator rotate the reduced gear once; a microswitch linked to the reduced gear generates electrical pulses, which are then counted to calculate the average wind speed over a ten-minute time period. This is a combination of the generator type and the pulse generator type.

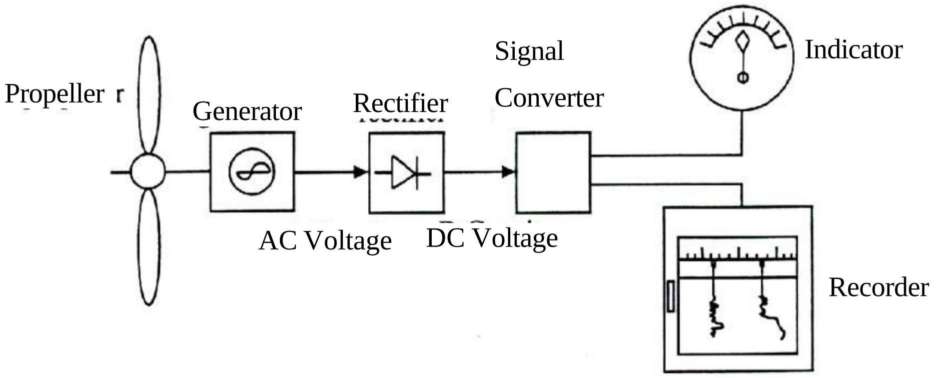


Figure 4.14 Diagram of signal flow

This type of anemometer, called a wind-passage propeller anemometer, ascertains wind speed by dividing the wind passage by the number of time units in a certain period. It is advantageous in that that the average wind speed can be measured even in very weak wind conditions when the propeller rotates only intermittently and it is difficult to obtain the average wind speed from the instantaneous wind speed.

Wind speed signals are output through the slip rings, the brushes and the terminal at the bottom of the stand. These slip rings send electrical signals from the rotor through the brushes. If there is a contact fault between the slip rings and the brushes due to contamination or wear, pulse-shaped noises will occur and the wind speed measurement may have errors. Extra care must therefore be taken with maintenance for the slip rings and brushes.

2) Pulse Generator-type Propeller Anemometers

A pulse generator-type propeller anemometer basically has the same external appearance as a generator-type propeller anemometer. The optical pulse generator type generates voltage pulses using a chopper disk that is directly coupled to the propeller shaft and a photocoupler.

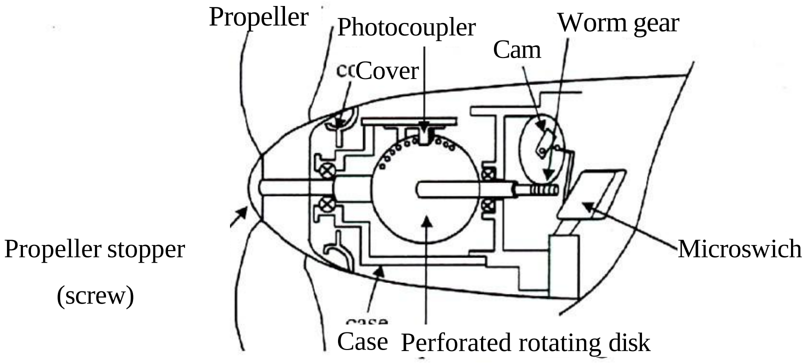


Figure 4.15 Pulse generator-type propeller anemometer

As shown in Figure 4.15, the wind speed sensor consists of a chopper disk and a photocoupler (i.e., a semiconductor device to convert light to electrical signals). It is essentially a light-emitting diode and a phototransistor situated facing each other, placed inside a mold and sealed.

The chopper disk is positioned so as to interrupt the optical axis of the photocoupler. A number of holes are made along the periphery of the disk so that it allows the passage of or interrupts a beam of light between the emitting and receiving devices of the photocoupler. When the phototransistor receives the beam of light, a voltage pulse is generated. The number of pulses for each unit time depends on the number of holes (24, 48, 60, etc., per revolution), and a number of pulse signals proportional to the wind speed is output. These pulse signals are sampled every 0.25 seconds, and the average value of the samples over a 3-second period (12 samples) is taken as the instantaneous wind speed.

The average wind speed over a ten-minute period is obtained using the wind-passage method or the CR integrated-circuit method of calculating generated pulses in real time with a microprocessor. In the case of the method with the microprocessor, pulse signals sampled every 0.25 seconds are processed to obtain the average value over a 1-minute period (20 instantaneous values are sampled), and this value is further averaged to obtain an overlapping average for a 10-minute period.

As the pulse signals output from the optical pulse generator type are digital, they are suitable for computer processing. They are converted to DC analogue signals using a D/A converter for indication or recording on analogue devices.

Another method of signal transmission is to use optical fibers to transmit pulse signals. A beam of light is emitted onto the chopper disk, and the optical pulses chopped by it are directly transmitted to the converter and the recorder through optical fiber. This method uses the same principle of wind-speed signal generation as the pulse generator type; the difference is in how the generated signals are transmitted.

[Comparison between the generator and pulse generator types]

The pulse generator type has the advantage of a lower starting threshold speed than the generator type. This stems from the fact that the weight of the chopper disk and other parts directly connected to the propeller shaft of the former can be made lighter than those of the latter type. By way of example, the starting threshold speed of the former type can be as low as about 0.5 m/s, while that of the latter type is about 1 m/s.

The overall weight of the propeller shaft in the pulse generator type can be made light, and consequently the moment of inertia becomes small. This makes it superior to the generator type in terms of its response to wind speed.

Furthermore, in the case of the generator type, the resistance of the signal cable may cause measurement errors because an AC current is carried from the anemometer to the indicator/recorder. The measurement accuracy of the pulse generator type, however, is not affected as long as a pulse frequency is detected. This applies even when the pulse amplitude becomes small due to the resistance of the signal cable.

While both the generator type and the pulse generator type use a generator, signal cables and electrical circuits (all of which are electrical conductors), another pulse generator type uses optical fiber, which does not conduct electricity. This type is resistant to lightning, and is suited for use in areas that need to be explosion-proof such as high-voltage substations and petroleum industrial complexes.

4.2.3.3 Response Characteristics of Rotating Anemometers

The response characteristics of an anemometer are determined by its starting threshold and its damping oscillation properties. An anemometer that immediately starts to rotate when the wind starts blowing and immediately halts when the wind stops is said to have good response characteristics. In the case of rotating anemometers, however, the mechanism does not allow the frictional force of the rotating axis to be reduced and the moment of inertia cannot be zero; accordingly, delayed response to changes in wind speed occurs. This delay is a source of errors in wind speed measurement.

The response characteristics differ between cases when the wind speed increases and when it decreases; for increases, the response time is shorter than for decreases. Graph 1 in Figure 4.16 shows the response when the wind speed suddenly increases from V_1 to V_2. There is a delay of t_1 in Curve ① until the indication reaches the level of $V_{2,}$ while Curve ② indicates a delay of t_2. If the wind speed suddenly decreases from V_2 to V_1 as shown in Graph 2, the rotating axis does not stop immediately because of the moment of inertia and the dynamic friction of the rotating axis. As a result, delays of t_3 and t_4 occur. In both graphs 1 and 2, the response characteristics of Curve ① are better than those of Curve ②. The curves in Graph 1 are called acceleration curves, and those in Graph 2 are called deceleration curves.

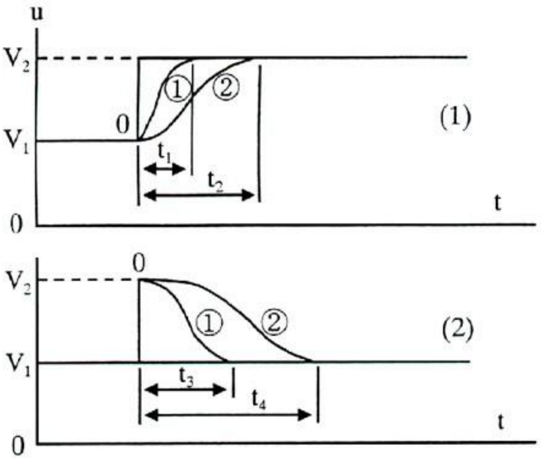


Figure 4.16 Acceleration and deceleration curves

A rotating anemometer has response characteristics such as t_1 (or t_2) < t_3 (or t_4) in the acceleration and deceleration curves shown in Figure 4.16. As its response is faster when the wind speed increases than when it decreases, the average wind speed it measures is a little higher than the true average.

The response characteristics of anemometers examined in a wind tunnel are shown in Figure 4.17, in which the solid lines show acceleration curves and the broken lines show deceleration curves at 5 m/s, 10m/s and 20 m/s, respectively. τ_1 and τ_2 are the time constants for each wind speed when the speed increases and decreases, respectively. As described above, τ_1 is generally smaller then τ_2. Provided that the wind speed is v and the time delay coefficient is the time constant τ, the value ($v \times \tau$) remains almost constant, and is termed the response length. As the time constant of a rotating anemometer varies with the wind speed and whether it increases or decreases, the response characteristics cannot be evaluated from the time constant alone. Accordingly, the response length is used as a measure to determine these characteristics. The smaller the response length, the better the response characteristics of the anemometer.

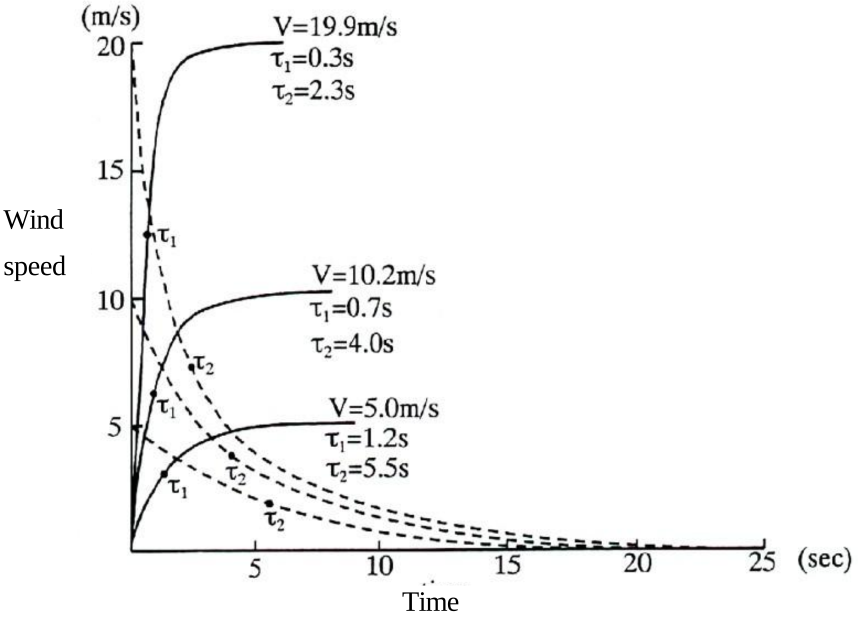


Figure 4.17 Anemometer response characteristics

4.2.3.4 Off-axis Response Characteristics of Rotating Anemometers

In wind speed measurement, it is assumed that the anemometer is exposed in a flat, open location and that it measures horizontal wind. This section describes the off-axis response characteristics of propeller and cup anemometers in relation to an exposed place with changes in the wind direction.

Figure 4.18 shows the off-axis response characteristics of propeller and cup anemometers examined in a wind tunnel. The vertical axis shows the ratio of measured speed when an anemometer is set laterally to the value at its normal position to the wind; the ratio is 1 when it is positioned facing the wind flow directly (i.e., when the angle is zero). The solid line shows the propeller anemometer’s off-axis response, and the dotted line shows that of the cup anemometer.

When an updraft or a downdraft (oblique flow) blows against the cup anemometer, vertical velocity fluctuations can cause overspeeding of the equipment as a result of reduced cup interference from the oblique flow. It is reported that the total overspeed can be as much as 10 per cent with some designs and wind conditions (cup anemometers at a height of 10 m with a response length of 5 m over very rough terrain).

On the other hand, when a propeller anemometer is exposed in oblique flow, the vane does not respond to the vertical component of wind. The indicated wind speed therefore decreases in proportion to the cosine of the oblique flow's angle. When observations are made with a propeller anemometer in oblique winds, only their horizontal component is measured. Accordingly, a propeller anemometer has virtually no vertical-component overspeed.

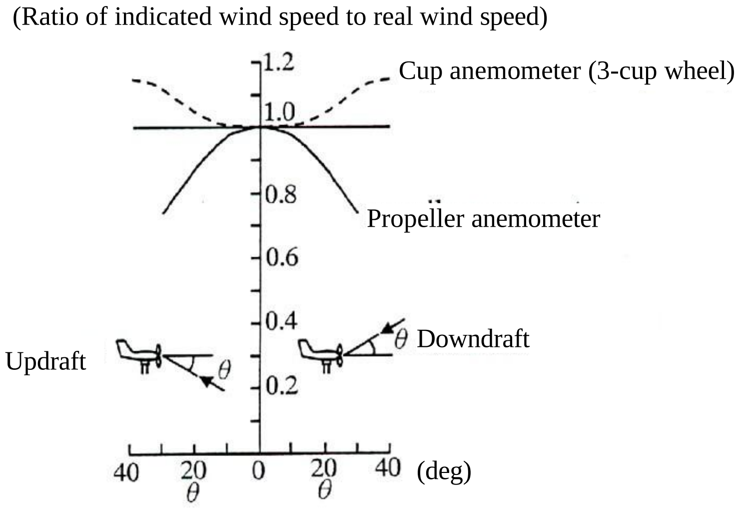


Figure 4.18 Off-axis response

4.2.4 Other Anemometers

In addition to the rotating anemometers (propeller and cup anemometers) described in the previous sections, there are other types that use different measurement methods, principles and ranges of wind speed. Figure 4.19 shows some examples, including the wind pressure anemometer and the sonic anemometer. This section gives an outline of the measurement principles and features of these devices.

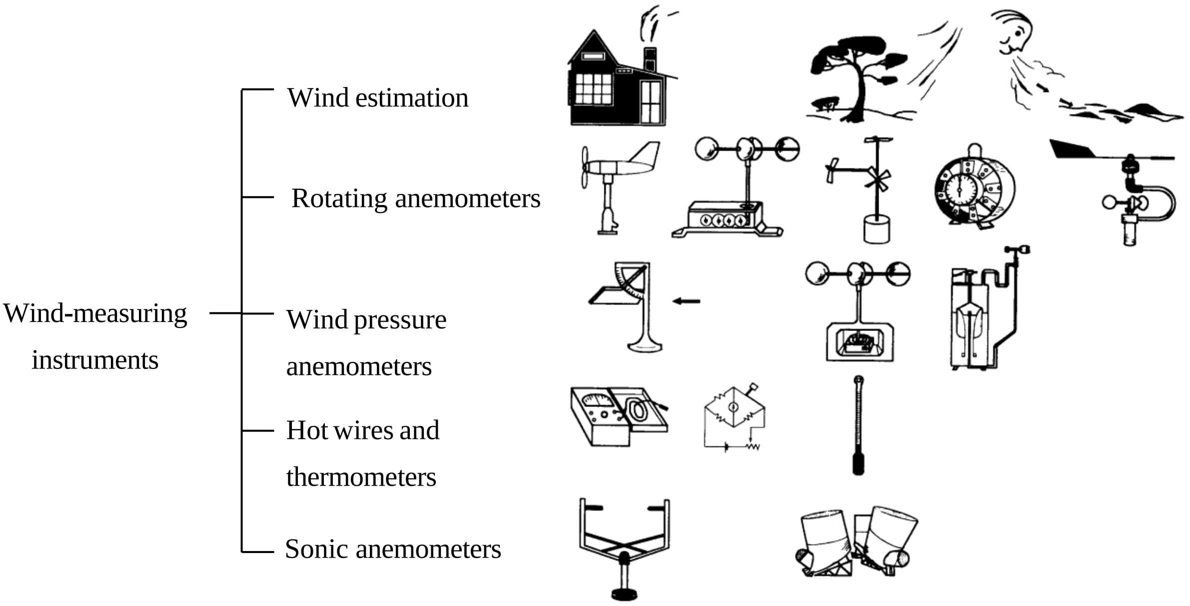


Figure 4.19 Wind-measuring instruments

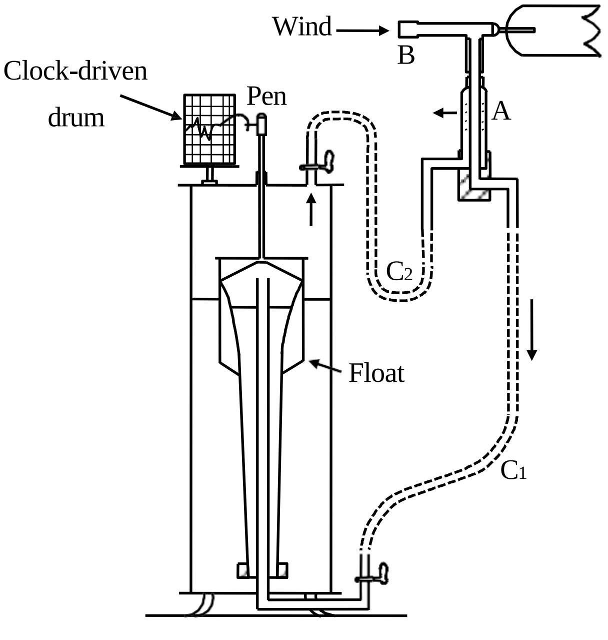
4.2.4.1 Method Using Wind Pressure Measurement

(1) Dines Anemographs

A Dines anemograph measures wind pressure to ascertain instantaneous wind speed. A single-plate vane is fixed to a pitot tube to allow its sensor to face the wind directly at all times as shown in Figure 4.20. There is an inlet hole B at the end of the pitot tube to measure dynamic pressure and a row of small holes A along the periphery of the tube at equal intervals to measure static pressure. The pressure values at B (dynamic pressure) and A (static pressure) caused by wind are induced through two pipes C_1 and C_2 into the inside and outside of a uniquely shaped float in a column of water. The upward and downward movement of the float is recorded on a clock-driven drum to represent instantaneous wind speeds.

This instrument has poor response to very weak wind conditions and rapid wind fluctuations. Additionally, because the difference between dynamic and static pressure is affected by air density, it is necessary to compensate changes in temperature. It is also necessary to prevent the water from freezing and exclude vibration to ensure that the float functions as intended in the water.

Measurement range: 0 to 60 m/s
Measurement accuracy: ±0.5 m/s



A: static pressure
B: dynamic pressure
C_1: dynamic-pressure tube
C_2: static-pressure tube

Figure 4.20
Dines (pressure-tube) anemograph

4.2.4.2 Method Using Heat Radiation

(1) Hot-wire Anemometers/Thermistor Anemometers

A hot-wire anemometer measures wind speed based on the theory that when a hot metal wire is exposed to wind and then cooled, its electrical resistance changes (Figure 4.21). Platinum wire is generally the type used for this purpose. As these anemometers have a small sensor part, they are suitable for wind speed measurement in confined environments.

This type of anemometer has a bridge circuit with a hot wire (the sensor) fitted on one side of the bridge. As wind blows against it, its temperature decreases and its electrical resistance changes; this creates an imbalance in the bridge and causes an electrical current to flow. The relationship between the current and the wind speed is predefined, and the current is converted to a wind speed value.

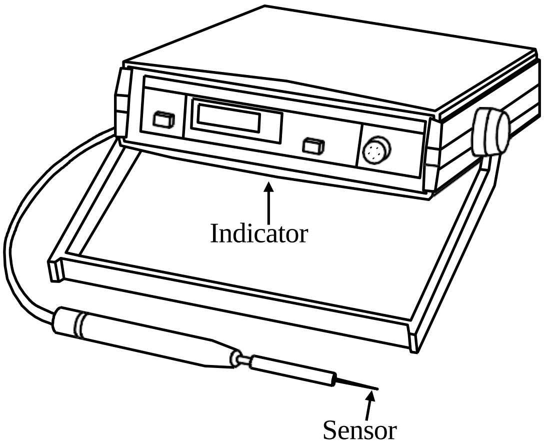


Figure 4.21 Thermistor anemometer

Another type of hot-wire anemometer that uses a thermistor device rather than a platinum wire has recently been introduced. The advantage of this new type is that it features superior sensitivity and response characteristics even in weak-wind conditions. However, if rain, snow or mist touch the sensor, large measurement errors may arise; it is therefore not suitable for outdoor use and cannot be used as a meteorological measuring instrument.

Measurement range:	0 to 1 m/s, 0 to 10 m/s, 0 to 50 m/s and various other ranges
Measurement accuracy:	±2% to ±3% in each respective measurement range

4.2.4.3 Method Using Sound Propagation

(1) Sonic Anemometers

Ultrasonic waves of more than 20 kHz that are inaudible to humans propagate at a speed of about 340 m/s in wind-free conditions. Sonic speed changes slightly in wind; sound waves propagate at a higher (lower) speed in the same (opposite) direction as its movement. A sonic anemometer leverages this relationship between wind and sound-wave propagation (Figure 4.22).

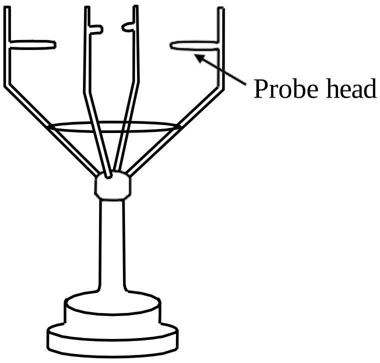


Figure 4.22
Sonic anemometer

A sonic anemometer has two pairs of sonic transmitting/receiving devices (heads) fixed facing each other across a specified span. Ultrasonic wave pulse signals are repeatedly emitted alternately from each pair of heads at certain time intervals. The propagation times of the ultrasonic pulses in opposite directions are measured; the wind speed is calculated in each direction, and the wind direction and speed are derived through vector synthesis. As the speed of sound in air depends on the temperature, measuring techniques have been developed to minimize this influence.

Because sonic anemometers have no moving parts to be actuated by wind force, the concept of a starting threshold speed is not applicable; such devices provide wind speed measurement from calm conditions upward. They also respond much more quickly to changes in wind direction and speed than rotating anemometers.

Measurement range:	0 to 60 m/s
Measurement accuracy:	±0.2 m/s

(2) SODAR (Sound Detection and Ranging)

The pitch of an ambulance siren or a train sounds higher when approaching the listener than when moving away from him or her. The phenomenon whereby sounds appear to have a higher or lower pitch than their actual frequency is known as the Doppler effect.

A SODAR device uses sound-wave deviation to measure upper-air wind speeds (Figure 4.23). It emits audible sounds (in a range from 1 to 6 kHz) from its transmitter in three directions (vertical, obliquely upward in a north-south direction and obliquely upward in an east-west direction) and monitors their return as they are scattered by air-mass density fluctuations. By detecting the difference between the frequency of the emitted sound waves and that of the ones that return (known as Doppler shift), the average movement of an air mass (i.e., the three directional components of wind) can be measured.

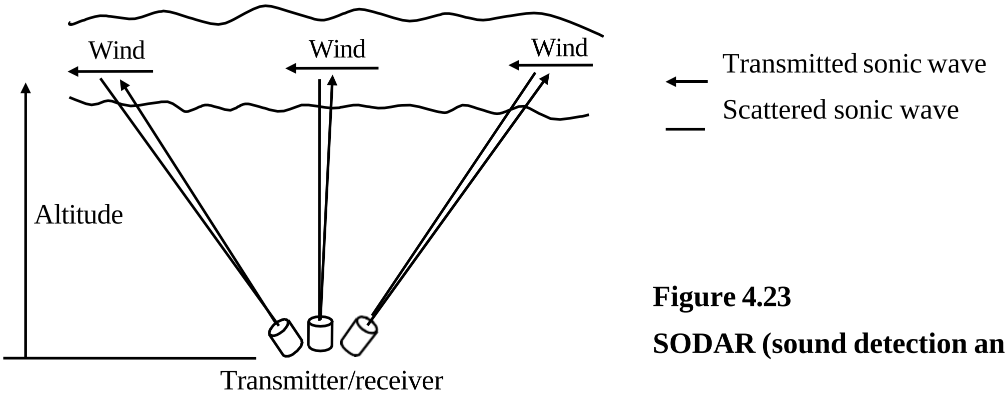


Figure 4.23
SODAR (sound detection and ranging)

This instrument is advantageous in that it can continuously measure winds at altitudes of 500 to 600 meters.

4.2.4.4 Method Using Radio Waves

(1) Wind Profilers

While SODAR uses the Doppler effect of sound waves, a wind profiler uses the Doppler effect of radio waves. As shown in Figure 4.24, it emits radio waves from its transmitter in three directions upward into the air and monitors their return as they become scattered by fluctuations in the refractive index caused by turbulent flow in the air. By detecting the difference between the frequency of the emitted radio waves and that of the ones that return, it can measure wind components in three directions.

The altitude to which a wind profiler can measure depends on the frequency of the radio waves used. In the 400-MHz band, winds at altitudes from 0.5 to about 16 km can be measured continuously.

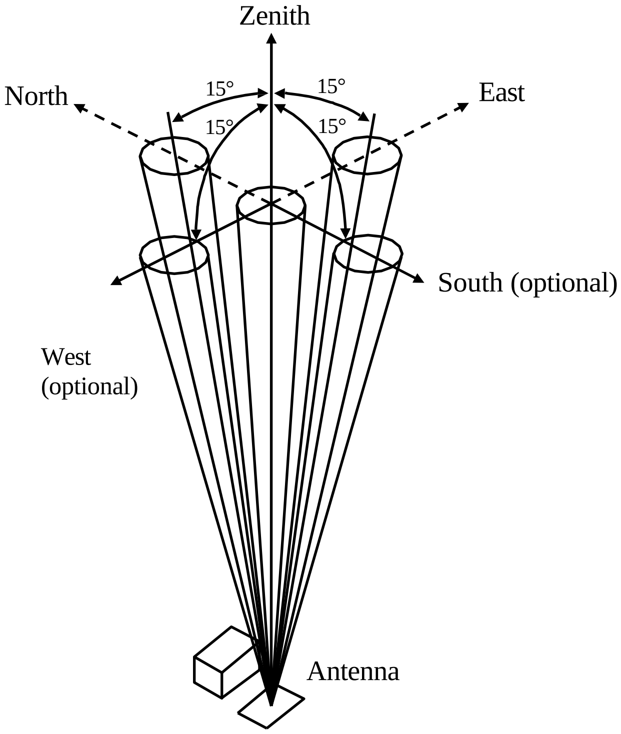


Figure 4.24 Wind profiler

(2) Doppler Radars

A function to measure Doppler shift in radio waves is added to a meteorological radar to create a weather Doppler radar. As shown in Figure 4.25, this device emits radio waves and monitors their return as they are reflected by precipitating particles such as raindrops or snowflakes. By detecting the difference between the frequency of the emitted radio waves and that of the ones that return, it can measure the distribution of wind speed elements such as divergence and convergence. In Doppler radar usage, the movement speeds of precipitating particles are considered to be equal to the wind speed in the air.

SODAR and wind profilers measure wind speeds by capturing echoes reflected as a result of upper-air density fluctuations. While they can make measurements continuously, Doppler radars have the disadvantage of not being able to take measurements where there are no precipitating particles.

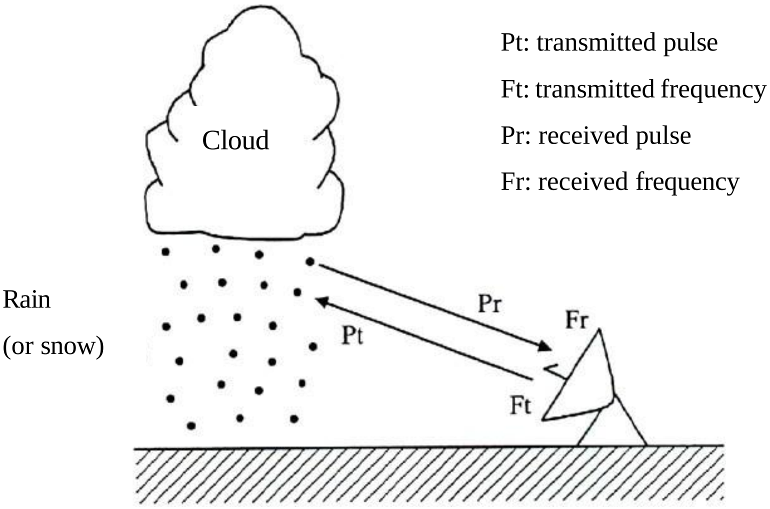


Figure 4.25 Doppler radar

4.3 Maintenance and Repair

As anemometer sensors operate in outdoor environments and are exposed to severe weather conditions, they deteriorate relatively quickly. To ensure stable, high-accuracy observation, anemometer maintenance should be carried out periodically.

This section describes general points to note when performing maintenance and repairing the sensors of anemometers. Strictly speaking, it is not possible to repair anemometers on site. If cups, propellers or bearings that may affect rotation characteristics are serviced or repaired, the device must be recalibrated. In principle, repairs and calibrations must be carried out by the manufacturer or a Meteorological Instrument Center in the relevant country, where the various standard instruments and calibration/testing equipment necessary are available.

4.3.1 Maintenance and Repair of Rotating Anemometers

Check item	Problem	Repair
External appearance	* Cup dents, arm deformation * Propeller deformation, wind-direction plate damage	* Badly deformed parts must be replaced. Slightly deformed parts can be repaired, but must be subjected to a rotational balance test. * It is not possible to repair such parts on site. Replacement is necessary.
Setup conditions	* Out-of-level mount * Wind-direction deviation	* Restore level status using a spirit level. * Orient the anemometer to the reference direction (usually north).
Unusual sounds	* Creaking sounds from rotary parts or lack of rotation at low wind speeds	* Bearings may be out of oil, worn or badly deformed. Dismantle the anemometer, clean bearings with gasoline and lubricate them. Bearings with significant wear must be replaced. * Overhaul the anemometer, clean all parts and lubricate them once a year.
Deterioration in sensitivity	* Wear on generator brushes or slip-ring contamination	* When overhauling an anemometer as described above, clean the brushes and slip rings.

4.3.2 Other Points to Note

(1) Cable Damage Caused by Small Animals

On agricultural land such as forests and fields, small animals including field mice, rabbits and squirrels may damage cable coverings or even break cables. Accordingly, it is advisable to string cables high above the ground. If buried in the ground, they should be placed at a depth of 30 cm or more to avoid the leaf mold layer. In buildings too, the same precautions should be taken to guard against damage caused by mice.

(2) Clearing Snow and Ice

Snow and ice may adhere to anemometers in cold climates. If exposed to snow or low temperatures with no wind, rotating parts may become frozen. As anemometers may also be deformed by the weight of snow or ice, such build-up must be cleared periodically.

It is advisable to provide artificial heating for anemometers operating in such environments.

4.4 Calibration

Accurate anemometer calibration can only be performed in a wind tunnel. However, the installation of such a facility involves tremendous investment, and its setup and maintenance are not easy tasks. This section describes some simple methods of checking anemometer operation to achieve the minimum required level of performance. An outline of the wind tunnel used by the Japan Meteorological Agency is also given.

4.4.1 Comparison by Beaufort Scale Observation

Comparing wind speeds measured with an anemometer to Beaufort Scale observation is the simplest method. However, as it provides only a rough estimation, its accuracy cannot be guaranteed.

4.4.2 Starting-threshold Torque Measurement

The torque of the starting threshold for a wind vane or anemometer is determined at the design and manufacture stages of each model. When a new instrument is introduced, its torque value should be checked with the manufacturer, or the torque at the starting threshold for the wind speed and the wind direction should be measured. The relevant data should be kept for reference, and subsequent instrument checks should be carried out with reference to these values. A tension gauge is used to measure the starting-threshold torque. Take several measurements and use the average as this torque value.

Another simple method of measuring starting-threshold torque is to use a weight equivalent to this torque value.

(1) Starting-threshold torque measurement using a tension-gauge

a. Place a cup anemometer horizontally in a wind-free indoor environment and connect it to a tension gauge with a string of about 50 cm in length as shown in Figure 4.26.

b. Slowly pull the tension gauge horizontally in the direction of the cup anemometer’s rotation. Record the reading on the meter when the cup starts rotating.

c. After repeating Step b several times, average the measured values to obtain the starting-threshold torque.

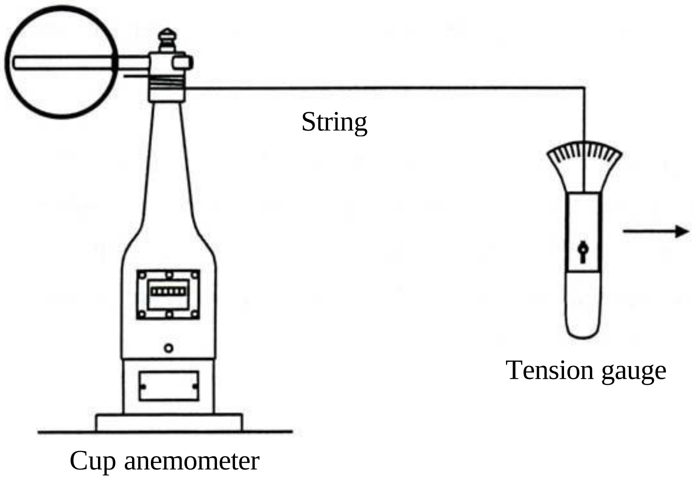


Figure 4.26
Measurement of starting threshold torque (wind speed axis) with a tension gauge

(2) Testing of wind-direction measurement initiation using a weight

a. Prepare a piece of string measuring about 1 m in length and a weight of about 35 g.

b As shown in Figure 4.27, set the anemometer horizontally, wind the string several times around the supporting shaft and hang the weight at the end of the string. Check the wind-direction axis to ensure that rotation starts smoothly in all directions.

(3) Testing of wind-speed measurement initiation using a small weight

a. Prepare a piece of string measuring about 1 m in length and a weight of about 7 g.

b. As shown in Figure 4.28, set the anemometer vertically. Detach the propeller and wind the string around its shaft. Hang the weight at the end of the string and check that the shaft rotates smoothly.

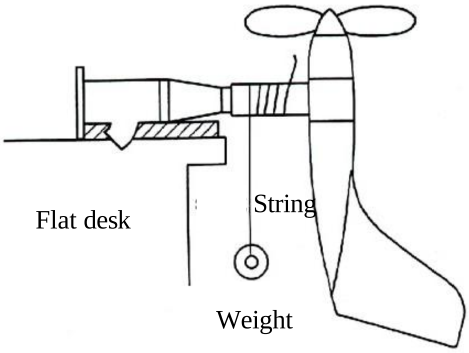


Figure 4.27
Propeller anemometer starting-threshold torque test (wind direction axis)

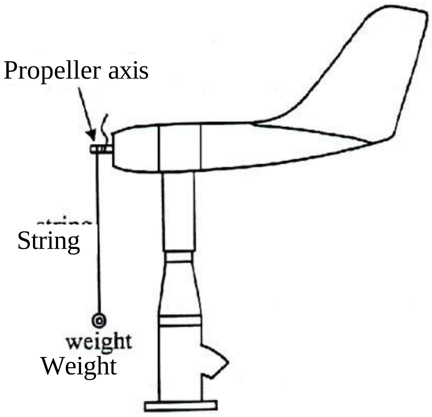


Figure 4.28
Propeller anemometer starting-threshold torque test (wind speed axis)

Starting-threshold torque measurements and tests conducted using weights to check wind direction and wind-speed measurement initiation are solely for the purpose of verifying smooth start-up in anemometers. They are not intended to guarantee the accuracy of calibration performed at individual wind speeds.

This section describes the measurement of starting-threshold torque and wind-direction/wind-speed measurement initiation for FF-6-type propeller anemometers, which are designed based on JMA’s specifications. The torque required for wind-speed measurement initiation naturally varies with the size of the wind direction axis and the propeller shaft.

[Japan Meteorological Agency Wind Tunnel]

A wind tunnel is a piece of wind-generating equipment used to verify the performance of anemometers and calibrate them. In 1943, the Japan Meteorological Agency installed the first wind tunnel of the Gottingen type. The diameter of its exit cone was 1 m, and the drive motor had a power of 75 kW. The wind speed range was from 1 to 75 m/s, and its body was made of wood. This wind tunnel was used until it was replaced in 1964 when the main building of JMA was rebuilt.

The current wind tunnel is made of steel and installed in the basement of the JMA building (Figure 4.29).

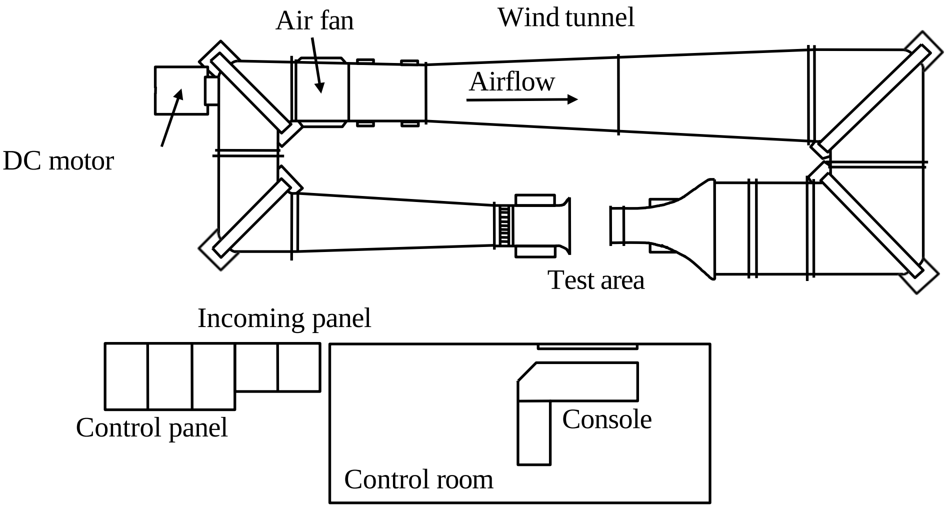


Figure 4.29 JMA wind tunnel layout

Main specifications

1) Type: Gottingen
2) Wind speed range: 0.35 to 90 m/s
3) Exit-cone diameter: 1.0 m
4) Air duct overall length: 47 m (including the working section of 1.2 m)
5) Air capacity: 230 to 4,240 m^3/min.
6) Fan: propeller-type single-stage axial fan (diameter: 1.7 m)
7) Rotation speed: 8.5 to 1,800 rpm
8) Motor: DC 440 V
9) Power: 200 kW
10) Control system: Thyristor Leonard

Control from the console

The console has various switches and gauges that the operator can use to select one of four operation modes: manual, automatic, step and fluctuating.

In automatic mode, 19 values can be set, allowing the operator to implement wind speeds automatically. In step mode, the wind speed is changed stepwise over selected speeds. Fluctuating mode implements speed changes with an amplitude around a given speed selectable within a range of 1 to 5 m/s and a period within a range of 5 to 15 seconds.

Power supply and controller

Three-phase 3,000 V, 50 Hz power is stepped down to 460 V using a distribution transformer. A Thyristor Leonard unit converts the AC voltage to a DC voltage to drive the DC motor. The feedback mechanism of a rotary encoder culed with the DC motor can adjust the motor’s rotation for any selected wind speed.

Fan-driving motor

The DC motor is directly connected to the 10-blade fan, which rotates in a range from 8.5 to 1,800 rpm and generates wind speeds from 0.35 m/s to 90 m/s.

Working section

The anemometer to be examined is mounted on the pedestal. A sonic anemometer is the standard instrument for wind speeds of less than 6 m/s. For wind speeds of more than 6 m/s, the pressure difference between the exit cone and the maximum diameter section is measured with a crystal pressure sensor, and is corrected using the ambient atmospheric pressure and air temperature at the exit cone as measured with a platinum-resistance thermometer. The signals from all the sensors are transmitted to the control console.

Data processing

Reference wind speeds are indicated on the gauges of the control console, and are simultaneously fed to a computer. The operator inputs the values measured with the anemometer to the computer, and the calibration results are printed out.

4.5 Others

4.5.1 Wind Instrument Exposure

Wind instruments are installed on open terrain 10 m above the ground. Open terrain is defined as an area where the distance between the anemometer and any obstruction is at least ten times the height of the obstruction.

In practice, however, it is often difficult to find ideal or even acceptable locations for wind measurements. Usually, wind sensors are exposed on a measuring tower or anemometer mast erected on the roof of a meteorological station or in its vicinity (Figure 4.30).

Even in locations where the standard exposure is not achieved, it is necessary to select a place where the environment meets the specified requirements (i.e., a flat, open location and a height of 10 m above the ground) as far as possible. The anemometer mast should be vertical to the ground, and the true north value of the wind-vane's sensor must be adjusted properly to the indicator or the recorder.

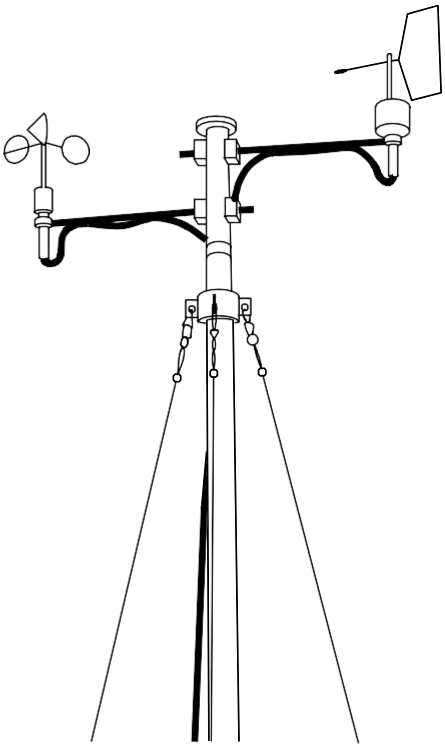


Figure 4.30 Anemometer mast

4.5.2 Wind Instrument Transportation

Regarding the transportation of instruments, refer to Chapter 1's Introduction to Meteorological Measuring Instruments and Transportation of Measuring Instruments.

4.6 Practical Training (Outline)

Disassembly and cleaning of a cup anemometer

Verifying the structure and working principles of a three-cup anemometer and performing disassembly and maintenance work

[Subjects to be covered in practical work]

(1) Checking of external appearance (presence of damage – cup dents, arm deformation, etc.)

(2) How to check the balance of cup wheels

(3) How to measure and check the starting-threshold torque

(4) How to check the overall condition and wear condition of bearings and replace them

(See the attached practical training manual.)

Chapter 6: Measurement of Atmospheric Pressure

CONTENTS

Chapter 6: Measurement of Atmospheric Pressure

5.1 Definition and Units

5.1.1 Definition

The atmospheric pressure is the force exerted by the weight of the Earth's atmosphere, expressed per unit area in a given horizontal cross-section. Thus, the atmospheric pressure is equal to the weight of a vertical column of air above the Earth's surface, extending to the outer limits of the atmosphere.

5.1.2 Units

In meteorology, atmospheric pressure is reported in hectopascals (hPa). 1 hPa is equal to 100 Pa, the pascal being the basic SI (System of International Unit) . 1 Pa is equal to 1 Newton per square meter (N/m^2). And 1 hPa is equal to 1mb that was used formerly.

The scales of all barometers used for meteorological purposes should be graduated in hPa. Some barometers are graduated in the unit inHg or mmHg. Under standard conditions, the pressure exerted by a pure mercury column which is 760 mm high is 1013.250 hPa, so the conversion factors are represented as follows:

1 hPa = 0.750062 mmHg;
1 mmHg = 1.333224 hPa.

And because of the relation between inch and mm (1 inch = 25.4 mm), the following conversion coefficients are provided:

1 hPa = 0.029530 inHg;
1 inHg = 33.8639 hPa;
1 mmHg = 0.03937008 inHg.

Pressure data measured with the barometer should preferably be expressed in hectopascals (hPa).

5.2 Principle of Atmospheric Pressure Measurement

5.2.1 Mercury Barometer

(1) Principle of mercury barometer

When a one-meter long, open ended glass tube is filled with mercury and is then turned upside down into a container filled with mercury, part of the mercury flows out of the glass tube into the container. "Torricellian vacuum" is then produced at the top of the glass tube and the mercury level stabilizes at approximately 76 cm from the mercury level in the container (See Figure 5.1). Torricelli's experiment revealed that such a height indicates the ambient atmospheric pressure.

The principle of mercury barometer is to measure atmospheric pressure from precise measurement of this height.

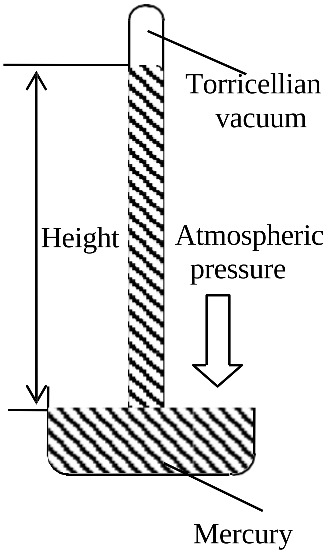


Figure 5.1 Torricelli's experiment

(2) Structure of the Fortin barometer

As shown in Figure 5.2, a mercury barometer consists of three main parts: the mercury cistern (right), the glass barometer tube (center) and the scale (left). The bottom of the mercury cistern is made of a wash-leather bag (sheepskin). The mercury level can be changed by rotating an adjusting screw. The barometer tube is secured with the wash-leather bag in the upper part of the mercury cistern in order to lead atmospheric pressure from the point at the bounded leather. An ivory pointer is put on the top of the mercury cistern, whose tip indicates the zero of the scale. When the level of the mercury touches the tip, the atmospheric pressure is read at the top of the mercury column. The precise height of the mercury column is measured with the vernier.

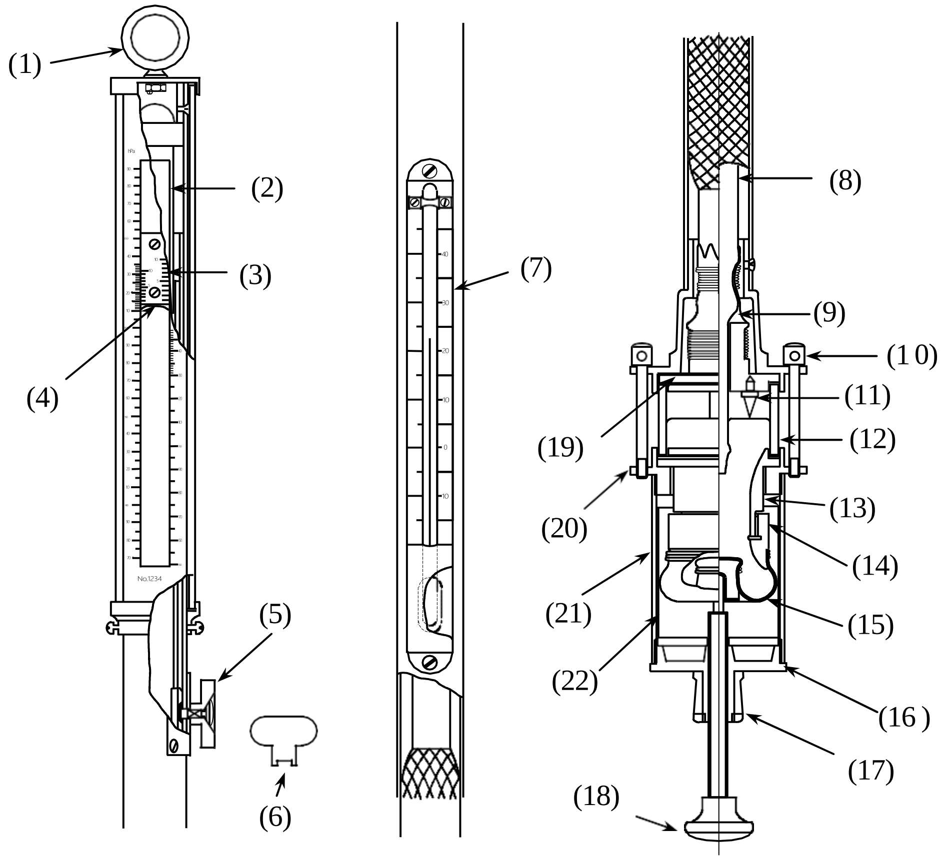


Figure 5.2 Structure of the Fortin barometer

(1) Hanger ring (2) Slot (3) Vernier (4) Top of the mercury column (5) Knob (6) Pin face wrench (7) Attached thermometer (8) Barometer tube (9) Vent wash-leather (10) Three screws (11) Ivory pointer (12) Glass cylinder (13) External thread wooden frame (14) Internal thread wooden frame (15) Wash-leather bag (16) Under cover (17) Screw bridge (18) Adjusting screw (19) Wooden base for leather washer (20) Metal frame (21) Brass cover (22) Mica plate.

The main body has a hanger hook at its top and is used to hang the barometer from a latch on a hanger plate. The bottom is secured to the screw bridge through a vertical axis pivoting link with three screws. Both the hanger hook and the screw bridge can be rotated while the barometer is set on the hanger plate. This allows verticality checks at any time.

A mica plate is wound inside the brass cylinder to prevent the direct contact between brass and the wash-leather bag. The plate serves as a heat insulator as well as prevents contamination, discoloration, and wear.

(3) Handling precautions for mercury

High-purity distilled and refined mercury is used in mercury barometers. When the mercury surface oxidizes, the interface between the surface and the ivory pointer becomes unclear. Heavily contaminated mercury surface requires cleaning. Since mercury is a toxic substance, it is necessary to pay attention to the following when handling mercury.

1) A container of mercury must be sealed tightly to prevent leakage and breakage. Do not put mercury into any metal containers as mercury reacts and amalgamates almost all metals except for iron.
2) The floor of the room where mercury is stored or used in large amounts should be shielded and laid with an impervious covering. It must not be stored together with other chemicals, especially with ammonia or acetylene.
3) Mercury has a relatively low boiling point of 357 °C, and produces dangerous poisonous gas if on fire. It must not be stored close to a heat source.
4) Check the mercury handling room and personnel periodically to make sure that the amount of mercury does not exceed the dangerous limit. (The environmental regulation on water contamination affecting personal health limits the total amount of mercury to 0.0005 mg/l.)

(4) Correction of barometer readings

The mercury barometer’s reading should be corrected to the one and the standard condition. Standard condition is defined as a temperature of 0 °C, where the density of mercury is 13.5951 g/cm^3 and a gravity acceleration of 980.665 cm/s^2.

During actual observation, the reading should be corrected for the index error, temperature correction, and gravity acceleration as follows:

(a) Corrections on index error

Individual mercury barometers include index errors (difference between the value indicated by an individual instrument and that of the standard). The index error is found by comparison with the standard, and the value is stated on a "comparison certificate".

(b) Corrections for temperature

The temperature correction means to correct a barometric reading, obtained at a certain temperature, to a value when mercury and graduation temperatures are 0 °C. The temperature of the attached thermometer is used for this purpose.

The height of the mercury column varies with temperature, even the atmospheric pressure is unchanged. The graduation of the barometer is engraved so that the correct pressure is indicated when temperature is 0 °C. In a case that when temperature is above 0 °C, the graduation expands and the measured value will be smaller than the true value. This effect of temperature must be corrected from these two aspects collectively.

Correction for the expansion and contraction of mercury is much larger than that for the expansion and contraction of the graduation.

The correction value for temperature *Ct* is expressed as follows:

$$Ct = -H\frac{(\mu - \lambda)t}{1 + \mu t}$$

where:

H hPa is the barometric reading after the correction for index error.

t °C is the temperature indicated by the attached thermometer.

μ is the volume expansion coefficient of mercury.

λ is the linear expansion coefficient of the tube.

There is a small difference in absolute values for correction between temperatures below and above 0 °C. The values for correction at temperatures above 0 °C are negative and those below 0 °C are positive.

(c) Corrections for gravity

Gravity affects the height of the mercury column. After the corrections for index error and temperature, the reading under the local acceleration of gravity has to be reduced to the one under the standard gravity acceleration. This is called corrections for gravity.

The gravity value for correction C_g is derived by:

$$C_g = H_0 - H = H\frac{g - g_0}{g_0}$$

where:

g_0 is the standard gravity acceleration.

g is the gravity acceleration at an observing point.

H is the barometric reading after the index error and temperature corrections

H_0 is the value already corrected for gravitation.

The gravity acceleration used in corrections for gravity value is calculated to the fifth decimal place, in m/s^2. When the gravity acceleration at the observing point is larger than the standard gravity acceleration, the gravity value for correction is positive. Otherwise, the value for correction is negative.

To use a barometer for regular observations at a particular location, a synthesis correction table that summarizes values for correction for index error, temperature and gravity should be used.

5.2.2 Aneroid Instruments

5.2.2.1 Aneroid Barometer

Aneroid barometers have lower accuracy than mercury barometers, but thanks to their compact and portable configuration, aneroid barometers are easier to handle and use, and suitable for self-recording.

An aneroid barometer measures the distortion of an evacuated, sealed elastic capsule inside with change in atmospheric pressure. The aneroid barometer consists of a barometer capsule, a spring to prevent the barometer capsule from being crushed by the atmospheric pressure, and gears and levers that intensify and transmit small amount of variations.

The elasticity of the barometer capsule varies depending on temperature. A bimetallic plate is used for temperature compensation. Once pressure distort an elastic body, it doesn't completely return to its original shape even after the pressure is relieved. Due to this characteristics called hysteresis, an error will arrive from the sharp change in atmospheric pressure and the error will be subjected to secular change. To prevent this, special materials are used for the elastic body. Stacked thin capsules or bellows are used in a number of barometers.

The appearance of an aneroid barometer is shown in Figure 5.3 and its structure is shown in Figure 5.4. Two barometer capsules facing each other are balanced around the pointer rotation axis. Two gears are used symmetrically to reduce vibrations. Two hair springs are attached to the gears to omit backlash from the pointer rotation gear.

The hole for adjusting pointer should be covered with a screw cap (if any) or with thin paper to keep out dust and insects.

When kept in good condition, the aneroid barometer has a difference of about ±0.2 hPa from a mercury barometer. The reading of the aneroid barometer should be corrected with the correction value against the mercury barometer, which is obtained at each observation with the mercury barometer. When reading the barometer, pat the glass surface slightly and read the value in the unit of 0.1 hPa, with close attention to the parallax error.

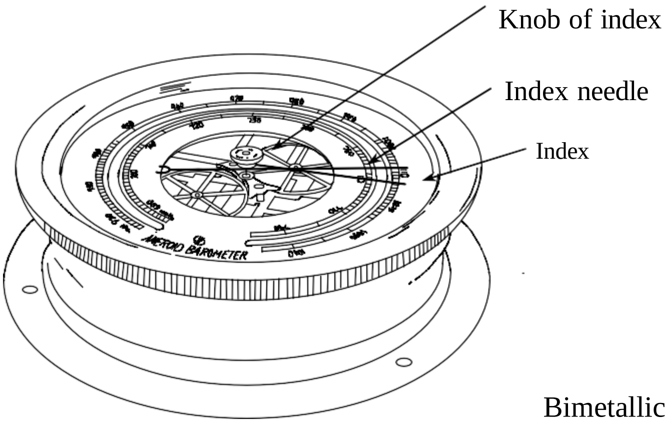


Figure 5.3 Appearance of the aneroid barometer

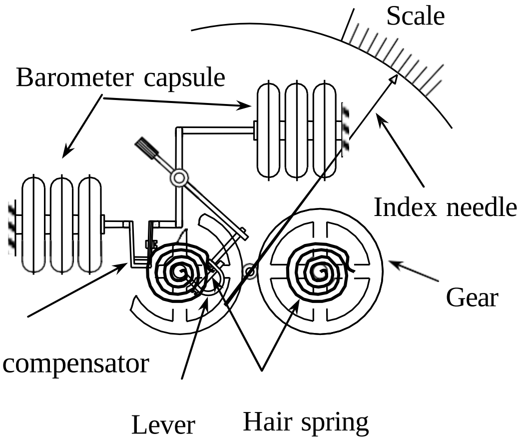


Figure 5.4 Mechanism of the aneroid barometer

5.2.2.2 Aneroid Barograph

The principle of the aneroid barograph is the same as that of the aneroid barometer, except for using a recording pen instead of the index needle. The structure of an aneroid barograph is shown in Figure 5.5.

The displacement of the barometer capsule (1) caused by the change in atmospheric pressure is transmitted to the recording pen (4) through the reed (2) and the lever (3). The recording pen (4) moves up and down on the side of the clock with recording drum (5) to record the changes in atmospheric pressure.

The barometer capsule (1) is vacuumed and balanced with atmospheric pressure through an internal helical spring. As the elastic modulus varies depending on temperature, temperature change on the equilibrium point is corrected by using a bimetallic plate (6) on the mounting part of the barometer capsule to compensate the effect of temperature.

The indicator can be adjusted by rotating the pointer adjusting knob (7) in the upper part of the barometer capsule (1) and by moving the pen arm (8) up and down.

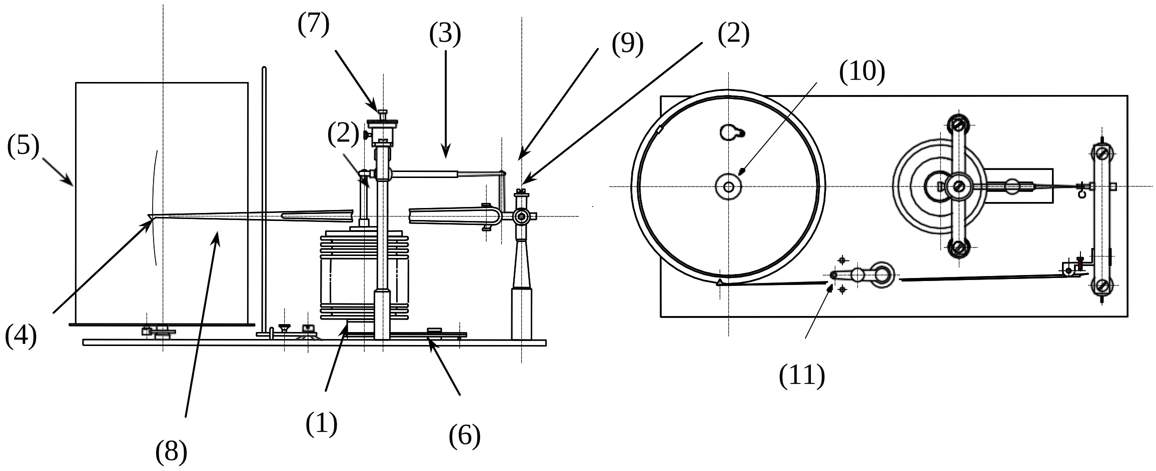


Figure 5.5 Structure of the aneroid barograph
(1) Barometer capsule (2) Reed (3) Lever (4) Recording pen (5) Clock-driven drum (6) Bimetallic compensator (7) Indicator adjusting knob (8) Pen arm (9) Pin with ring (10) Holding screw of the clock-driven drum (11) Gate suspension arm.

5.2.3 Electronic Barometer

Stable and continuous power supply is required to measure atmospheric pressure with an electronic barometer.

5.2.3.1 Cylindrical resonator barometer

Cylindrical resonator barometers measure atmospheric pressure by resonating a thin cylinder and reading the changes in resonance frequency caused by changes in atmospheric pressure.

The sensor is a metallic double cylinder with one end closed and the space of which between the outer and inner cylinders is vacuumed (See Figure 5.6). The natural frequency of the inner cylinder (cylindrical oscillator) changes depending on the pressure applied to its inside. The atmospheric pressure can be obtained by measuring this frequency.

This cylindrical oscillator is equipped with four piezo-electric elements, two of which are for driving and the others for detecting the resonance frequency (See Figure 5.7).

To eliminate the influence of temperature change, the cylindrical oscillator is provided with a temperature sensor for temperature correction.

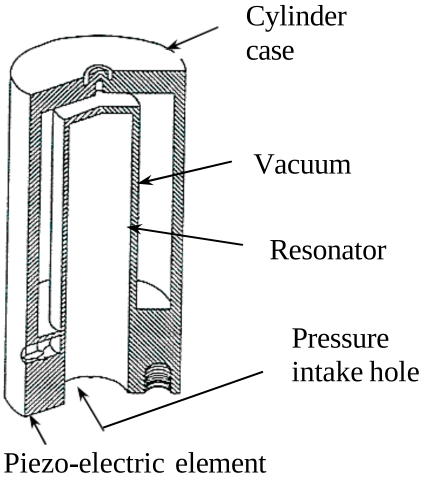


Figure 5.6 Cylinder of the cylindrical resonator barometer

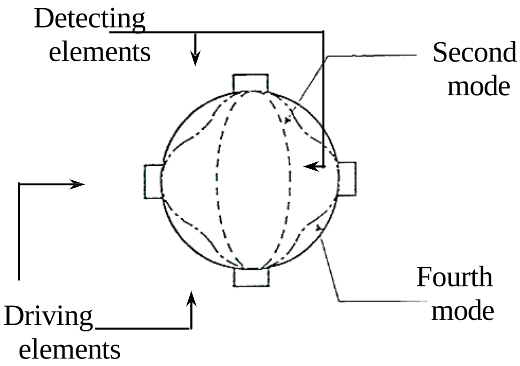


Figure 5.7 Resonance mode of detecting and driving elements

5.2.3.2 Electrostatic capacity barometer

This type of barometer has a pressure sensor in dimensions of some millimeters. It consists of silicon wafer to detect pressure, a silicon chip for substrate, and an insulating glass plate (See Figure 5.8). The silicon wafer to detect pressure is etched to form an electrode and a diaphragm, and a vacuum gap between the silicon and the glass plate is made.

The silicon chip for substrate is also etched to form the other electrode. These electrodes of silicon wafer and silicon chip separated by the vacuum gap form a kind of capacitor.

The shape of the diaphragm changes depending on atmospheric pressure, causing the vacuum gap to expand or contract. Such deformation causes the change in the electrostatic capacity of the gap and the electrodes. This slight change is detected as an electric signal and converted to atmospheric pressure.

This electrostatic capacity digital barometer features high precision and long-time stability.

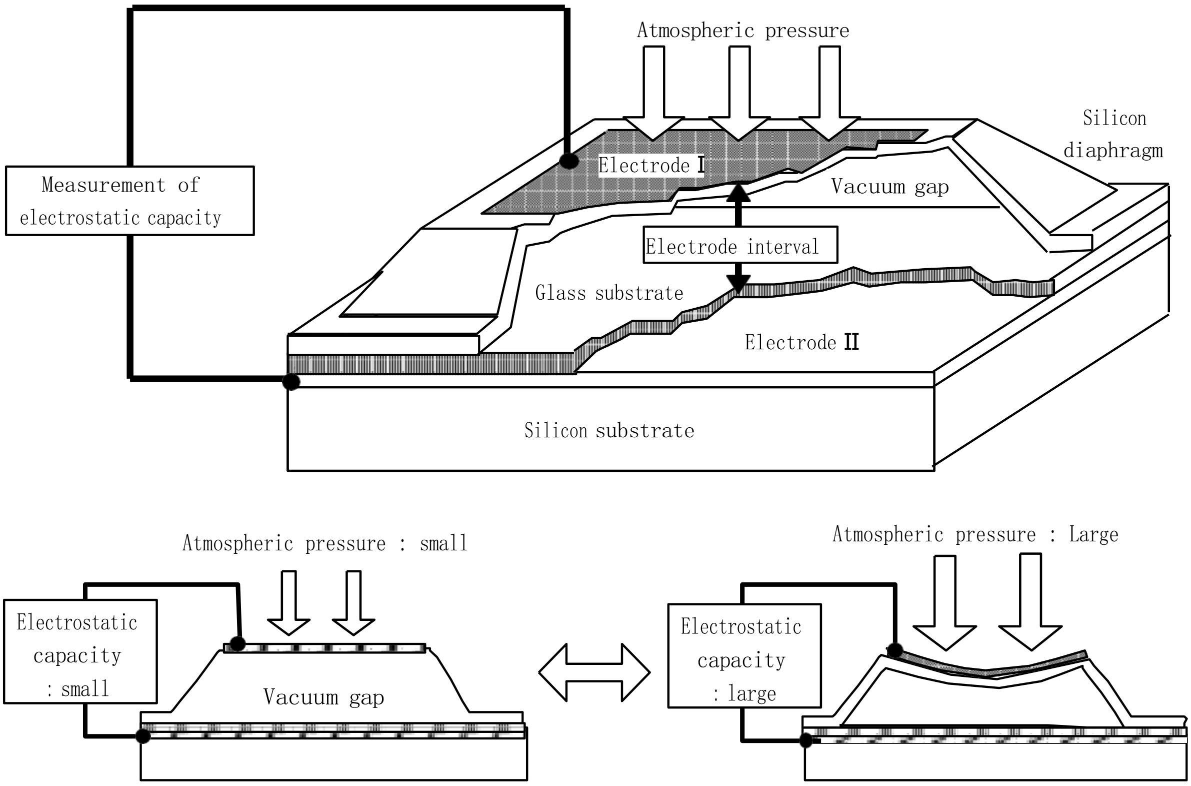


Figure 5.8 Pressure sensor of the electrostatic capacity barometer

5.2.4 Reduction to Mean Sea Level

To compare the atmospheric pressure value at a certain location to a value at another location, it is necessary to convert the values at the same referential altitude. It is internationally decided to use the mean sea level as the referential altitude, and the conversion is called reduction to mean sea level.

Various kinds of methods of the reduction are used in individual countries. For international comparisons, however, methods should be standardized to ensure data interchangeability. Two basic equations, hydrostatic equation and state of ideal gas equation are used in each country. Differences among the methods are found only in the ways to calculate the gravity acceleration and the mean virtual temperature.

When the vertical distribution of air temperature and humidity between the mean sea level and the observation point are known, reduction to mean sea level can be made accurately. However, the air temperature and humidity just at the observation point are generally known. Therefore, the atmospheric pressure at mean sea level is obtained assuming the standard vertical distribution of air temperature and humidity

Suppose there is a vertical air column from the observation point to the mean sea level. The relation between atmospheric pressure P at the observing point, in hPa, and atmospheric pressure P_0 at mean sea level, in hPa, is given by:

$$\ln\frac{P_0}{P}=\frac{1}{R}\int_0^Z\frac{g\,dz}{T_V}$$

where:

T_v is the virtual temperature of the vertical air column, in K.

R is the gas constant of dry air, in $\mathrm{Jkg^{-1}K^{-1}}$.

Z is the height from mean sea level to the barometer, in meters.

Assuming that "g" is constant and is equal to the gravity acceleration at the observing point. The mean of virtual temperature is given by:

$$T_{Vm}=\frac{Z}{\int_0^Z\frac{dz}{T_V}}$$

It results:

$$P_0=P\cdot\exp\left(\frac{gZ}{RT_{Vm}}\right)$$

Therefore, the reduction to mean sea level value ΔP is given by:

$$\Delta P=P_0-P=P\left(\exp\left(\frac{gZ}{RT_{Vm}}\right)-1\right)$$

Now T_{Vm} is expressed as: $T_{Vm}=273.15+t_m+\varepsilon_m$ (K), where t_m is the average temperature of the air column, ε_m is the effect of air humidity. Assuming the lapse rate of air temperature to be 0.5℃ /100m results:

$$t_m=t+0.005\cdot\left(Z/2\right)$$

where:

t is the air temperature at the observing point.

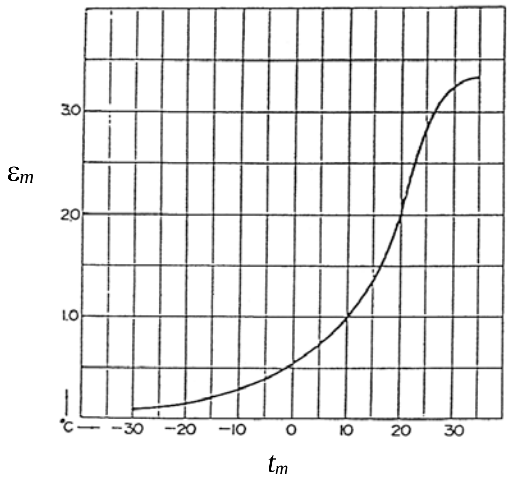


Figure 5.9 Relationship between ε_m and t_m

The value of ε_m is statistically determined as a function of the average air temperature. The relationship between t_m and ε_m is graphically shown in Figure 5.9. This is statistically derived from surface observation data obtained at eight meteorological observatories in Japan. This relationship is almost the same as that in the lower atmosphere under average conditions in Japan. The value of "*R*" is 287.05 $\mathrm{Jkg^{-1}K^{-1}}$. Use this formula to calculate the reduction to one decimal place to mean sea level value ΔP as a function of air temperature t and atmospheric pressure P at the observing point. It is convenient to tabulate the reductions in advance. The air temperature at the observing point t should be the one at the height of the barometer, but the air temperature at the observation field is used instead as the difference is negligible. Similarly, "*g*" should be the average value down to the mean sea level, but its influence is also negligible.

$\varepsilon_m = (\mathrm{A}t_m+\mathrm{B})\, t_m + \mathrm{C}$
$t_m < -30.0\ ^\circ\mathrm{C}$; $\varepsilon_m = 0.09$
$-30.0 \le t_m < 0.0$; $\mathrm{A} = 0.000489,\ \mathrm{B} = 0.0300,\ \mathrm{C} = 0.550$
$0.0 \le t_m < 20.0$; $\mathrm{A} = 0.002850,\ \mathrm{B} = 0.0165,\ \mathrm{C} = 0.550$
$20.0 \le t_m < 33.8$; $\mathrm{A} = -0.006933,\ \mathrm{B} = 0.4687,\ \mathrm{C} = -4.580$
$33.8 \le t_m$; $\varepsilon_m = 3.34$

5.3 Maintenance

5.3.1 5.3.1 Maintenance of the Mercury Barometer

The maintenance of mercury barometers is carried out in the following ways:

1) Once a month, brush dust off the outer surface with a soft brush, and wipe metal and glass parts with a soft cloth. Check the barometer for flaws and cracks.
2) If dirt collects on the mercury level where the mercury comes into contact with the ivory pointer, turn the adjusting screw as shown in Figure 5.2 to lower level by approximately 3 mm. Restore the adjusting screw, and dirt will be removed. At this time, be careful not to shake the main body in an attempt to remove the dirt, as the inside of the glass tube may become dirty above the mercury level, resulting in unclear readings.
3) The degree of vacuum should not be checked unless it is definitely necessary to do.

5.3.2 Aneroid Instruments

5.3.2.1 Aneroid barometer

Clean the surface or the glass part of the aneroid barometer with a soft cloth or brush every week. (See Figures 5.3 and 5.4.)

5.3.2.2 Aneroid barograph

Check the aneroid barograph as indicated in Chapter 2: Measurement of temperature, and when there is a difference of ±0.3 hPa or more between the reading of the aneroid barograph and that of the mercury barometer, turn the indicator adjusting screw (7) to adjust the indicator in Figure 5.5.

5.3.3 Electronic Barometer

5.3.3.1 Cylindrical resonator barometer

As the humid air in the sensor of the cylindrical resonator barometer results in an error of approximately ±0.1 hPa in the pressure reading. Replace the desiccant enclosed near the sensor every month.

5.3.3.2 Electrostatic capacity barometer

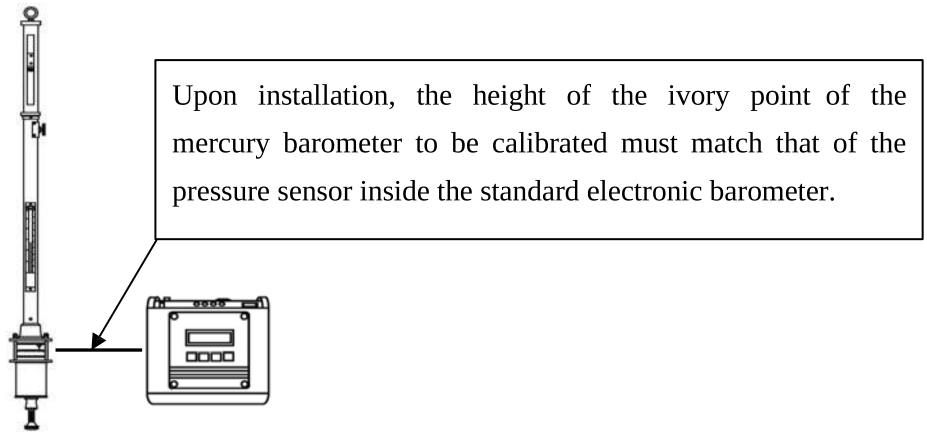
Electrostatic capacity barometers have high performance and stability, requiring no daily maintenance.

5.4 Calibration

5.4.1 Mercury Barometer

5.4.1.1 Installation

As the structure of mercury barometers gives them low mobility, a standard electronic barometer is installed in their proximity for calibration. At the time of installation, it should be ensured that the height of the mercury barometer’s ivory point matches that of the pressure sensor inside the electronic barometer (Figure 5.10). Calibration can be performed a day after installation is complete.



Upon installation, the height of the ivory point of the mercury barometer to be calibrated must match that of the pressure sensor inside the standard electronic barometer.

5.4.1.2 Calibration

Calibration is performed under conditions of a pressure change of 1 hPa/h or less and a wind velocity of 3 m/s or less. For each calibration, 20+ atmospheric pressure readings should be taken with the standard electronic barometer and the mercury barometer to be calibrated. The numbers of readings of atmospheric pressure showing a tendency of increase and a tendency of decrease should be approximately identical. The same person must take all measurements to prevent reading errors.

Temperature correction and gravity correction must be applied to mercury barometer readings using the methods described in Section 5.2.1 Mercury barometers, (4) Correction of barometer readings, (b) Corrections for temperature, and (c) Corrections for gravity.

5.4.2 Aneroid Barometer

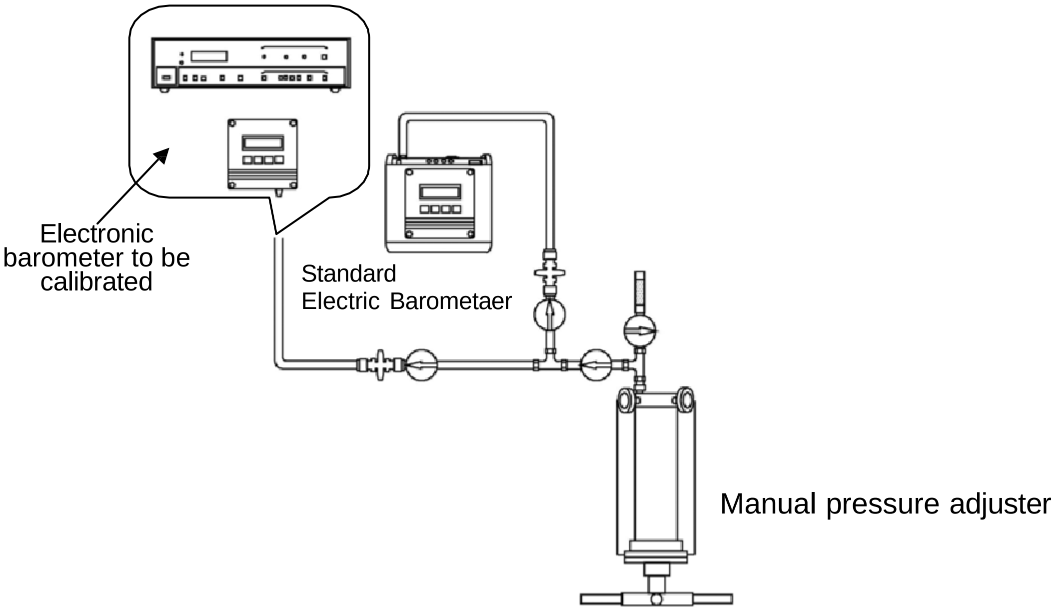
If aneroid barometer readings differ from those of the standard electrical barometer by ±0.3 hPa or more, the index knob shown in Figure 5.4 should be adjusted.

5.4.3 Electronic Barometer

(Cylindrical resonator barometer, Electrostatic capacity barometer)

5.4.3.1 Installation

For electronic barometer calibration, the barometer to be calibrated and the standard electronic barometer must be connected with a pipe, and a manual pressure adjuster must be used for setting as shown in Figure 5.11. Upon installation, the pressure sensors inside both barometers must be at the same height. Installation should be completed a day before calibration to allow the instruments to acclimatize to room temperature.



5.4.3.2 Pressure inspection

Prior to calibration, the pressure should be gradually changed throughout the entire calibration range a few times using the manual adjuster. Comparative measurement at the calibration points should then be performed as described below.

Comparative measurement must be performed at least three times each with upward and downward pressure changes. The difference between the readings of the standard barometer and the barometer to be calibrated at each point should be recorded, and the average of the difference at each point can be taken as the error index for each calibration point.

Calibration points: 880, 920, 960, 1,000, 1,040 (hPa)

*If the specified facilities for pressure inspection are not available, an alternative simplified method can be used in which the barometer to be calibrated and the standard electronic barometer are placed at the same height in the atmosphere. Approximately 20 barometer readings are then taken to determine the correction value at atmospheric pressure.

5.5 Repair

5.5.1 Mercury Barometer

When the difference in observation values increases between the mercury and the aneroid barometers and the mercury barometer appears to be defective, repair it following the instructions as described below (See Figure 5.2).

1) The difference increase is probably caused by the impaired vacuum or the loose mounting of the ivory pointer. When the vacuum becomes impaired, drain and refill the mercury. When the ivory pointer mounting part becomes loose, disassemble and screw it up tightly.
2) When the knob (5) used to move the vernier (3) comes loose and causes a large backlash when the graduation is adjusted, tighten two nuts on the knob with a special tool (pin face wrench) (6).
3) Do not lubricate the adjusting screw (18) and the knob (5) excessively. Excess oil will spread and melt paint varnish, causing sticky thread. It will stiffen the screw all the more. In addition, the oil will soak into the wash-leather bag (15) and the wooden part, and contaminate the mercury. When the adjusting screw (18) is stiff, it is probably because the screw is bent or the thread is dirty. In these cases, replace the screw or remove and clean it with a brush and cloth.
4) When the level of a mercury barometer seems to be not working correctly due to an earthquake, for example, loosen three screws of the vertical axis pivoting link. Check the level and tighten the screws again.

5.5.2 Aneroid Instruments

5.5.2.1 Aneroid barometer

The aneroid barometer is a very precise instrument, and it cannot be easily disassembled or repaired on site.

5.5.2.2 Aneroid barograph

Repair aneroid barographs according to the repair instructions in Chapter 2: Measurement of temperature. When irregular movements of the pen arm are noticeable, repair it as follows (See Figure 5.5).

1) Pull out the pin (with ring) (9) and the connecting pin. Clean pinholes on the barometer capsule (1), reed (2) and lever (3) with volatile oil or benzine, and remove old oil. Polish the inside of the holes with an oil-absorbing toothpick and apply a thin film of high-quality clock oil inside the holes before assembly.
2) Feel how the pivots rattle with hands. Remove one pivot at a time. Clear out old oil and dust. When the pivot is rusty, polish it evenly with a lathe or oilstone and lubricate it with clock oil, as mentioned above in 1), before assembly.
3) The reed (2) must be centered on the crack of the lever (3). If not, check the pin and the crack for distortion, and repair any defective parts before reassembly.
4) To repair the clock-driven drum (5), refer to the relevant section in Chapter 2: Measurement of temperature.

5.5.3 Electronic Barometer

Cylindrical resonator and electrostatic capacity barometers mainly consist of electric components, and they rarely have mechanical parts. Therefore, it is rarely possible to repair these barometers on site.

5.6 Transport

5.6.1 Mercury Barometer

(1) Method of transport

When transporting the mercury barometer, fill the vacuum part with mercury and turn the barometer upside down to prevent any air from entering. This also applies to indoor transport, regardless of distance. For long distance transport, carry it in a leather carrying case keeping the barometer in the upside down position.

(a) Removing the mercury barometer

To remove the mercury barometer from the hanger plate, softly turn the adjusting screw (18) (See Figure 5.2) until the mercury column reaches the top of the tube. It may be difficult to notice by only feeling the adjusting screw or listening to its metallic sound. So, pay careful attention to the mercury column movement while rotating the adjusting screw. If the cistern has an air vent, it must be closed tightly at this stage.

After turning the adjusting screw, loosen three screws of the vertical axis pivoting link. Remove the screw in the upper part of the hanger plate. Hold the main body firmly with both hands, and remove it from the hanger plate.

(b) Turning the mercury barometer upside down

After removing the mercury barometer from the hanger plate, tilt it slowly and turn it upside down.

(c) Storing the mercury barometer in a leather carrying case

Check the leather carrying case so the barometer will not come off, that the shoulder belt is not worn, and the cap can be tightened securely. When everything is checked out, put the barometer, which has been turned upside down in step (b), in the leather carrying case slowly. When the mercury cistern is about to enter the leather carrying case, grab the adjusting screw securely with one hand and lift up the leather carrying case with the other hand so that the top of the mercury barometer bottoms on the leather carrying case.

After putting the barometer into the leather case, fill cushioning material around the mercury cistern for support.

(2) Precautions of transport

When the temperature of the barometer rises during transport, the mercury expands and may break the glass tube or leak out. To prevent this, loosen the adjusting screw (18) one or two turns (See Figure 5.2) in advance.

Sling the leather carrying case over the shoulder, and do not swing it.

For long-time transport by rail or vessel, put the leather carrying case upright in a safe place so that the barometer is always upside down. If it is impossible to put the leather case upright, be careful not to allow it to tilt more than 30 degrees. For temporary placement during transport, put the leather case at a stable place so that it does not fall down accidentally.

Air transport of mercury and associated instruments are regulated by the International Air Transport Association (IATA).

5.6.2 Aneroid Instruments

Generally, aneroid instruments have a measuring range from 900 hPa to 1,050 hPa. Do not transport these barometers by air, as barometer capsules may break from exceeding its measuring range.

For transport of a clock-driven drums of the aneroid barograph, refer to Chapter 2: Measurement of temperature.

5.7 Installation

5.7.1 Mercury Barometer

(1) Checking the mercury barometer

After putting the mercury barometer out of the leather carrying case, check it for damage, distortion, and mercury leakage with keeping it reversed. After its integrity is confirmed, tighten the adjusting screw (18) (Figure 5.2) until it stops and the air is taken out.

(2) Turning the mercury barometer back to a vertical setting

After taking out the air by tightening the adjusting screw (18), hold the mercury barometer with both hands and turn it back to a vertical setting slowly. Then, turn the vernier knob (5) and check that it does not become fast nor run idle.

(3) Test for the presence of gas in the barometer tube

Holding the mercury barometer firmly with one hand, pat the brass cover (21) of the mercury cistern with fingers of the other hand a few times, and loosen the adjusting screw (18) a little. When the top of the mercury column (4) appears in the upper part of the slot (2), tighten the screw a half turn so that the top of the mercury column (4) is slightly hidden in the upper part of the slot (2). Holding the mercury barometer with both hands, tilt it slowly. While tilting the barometer to an angle of about 30 degrees, the mercury will reach the top of the barometer tube (8) and emit a metallic sound like a click. If the click is sharp and metallic, the mercury column has reached the top without meeting any gases. When performing this test, the operator should be aware of the danger of breaking the barometer tube by tilting the barometer too quickly.

(4) Checking the attached thermometer

Check the attached thermometer (7) for breakage or disconnection of mercury column.

(5) Checking the hanger plate

Check the integrity of the upper and lower milky white glasses, hanger hook, vertical axis pivoting link, and wall hanger hook of the hanger plate. Check the latch screw and the three vertical axis pivoting link screws for distortion or shortage.

(6) Installing the mercury barometer

The mercury barometer must be installed as vertically as possible to minimize reading error. Before installation, remove the attached thermometer and the latch screw, and loosen the centripetal screw. With the glass cylinder (12) filled with mercury, stand the barometer upright and insert the adjusting screw (18) into the center of the vertical axis pivoting link.

Next, hang the metal hook (1) from the hanger hook and attach the screw of the hanger hook. Using three screws, secure the vertical axis pivoting link to keep it in an up-right position.

Turn the adjusting screw (18) slowly until the mercury level in the mercury cistern is 1 mm below the ivory pointer. Do not lower the mercury level abruptly, as the air inside the brass cylinder (21) is compressed and leaks through the wash-leather bag to the mercury level, causing bubbles in the mercury tube (8). Make sure that no bubbles appear in the upper part of the mercury tube (8) during this process. If the wash-leather bag is too hard, the mercury level may not go down smoothly by loosening the screw. In such a case, pay close attention to a sudden fall in the mercury level. If the mercury level does not go down spontaneously, pat the adjusting screw (18) from below with the finger.

After the installment of the mercury barometer, reinstall the attached thermometer as before. Leave the barometer as is for at least a day for conditioning at room temperature.

5.7.2 Aneroid Instruments

5.7.2.1 Aneroid barometer

(1) Pre-install inspection

Before installing the aneroid barometer, check it for glass breakage. Make sure that the index (Figure 5.3) moves smoothly and stops at an arbitrary point. Shake the barometer slightly and listen to its internal sound to check for loose screws and nuts.

(2) Pre-install adjustment

Rotate the indicator adjusting knob to set the indicator to atmospheric pressure measured with a mercury barometer on site.

(3) Installing the aneroid barometer

The barometer should be installed inside the barometer room. If it is impossible, place the barometer in a place free from direct sunlight and extreme temperature changes. The barometer should be positioned in a place free from vibration and strong impacts. When installing the barometer on a pillar or wall, secure it tightly with wood screws to prevent it from falling.

A barometer specifically intended for horizontal installation should be used in its accessory case or wooden box for protection.

5.7.2.2 Aneroid Barograph

(1) Pre-install inspection

Before installing the aneroid barograph, check the main body (Figure 5.5) and the clock-driven drum (5) for breakage, distortion, loose or missing screws, and other disorders. If everything is fine, attach the clock-driven drum (5) to the main body. With the pin with ring (9) removed, make sure that the tip of the recording pen (4) aligns with the graduation line for time (curvature) of the recording chart. Make sure that the pen pressure is appropriate.

Insert the pin with ring (9) into the lever (3) and the reed (2). Turn the indicator adjusting knob (7) to adjust the reading to the atmospheric pressure measured with a mercury barometer on site. At this time, slightly vibrate it to make sure that the pen tip stays at the same point.

Finally, wind the spring of the clock-driven drum and make sure that it operates properly.

(2) Pre-install adjustment

Do not carelessly change the magnification on site, as it necessitates reinspection. Do not carelessly change the temperature correction bimetallic mounting position as well, as it affects the precision.

When the tip of the recording pen (4) does not align with the graduation line for time on the recording chart, the clock-driven drum may slant. Correct it referring to Chapter 2: Measurement of temperature.

(3) Installation of the aneroid barograph

As a general rule, the aneroid barograph should be positioned on a solid desk or table in the barometer room. Lay a rubber sheet or other cushion under the aneroid barograph to absorb vibrations of the building.

5.7.3 Electronic Barometer

Cylindrical resonator and electrostatic capacity barometers should be used according to operating instructions. Since they contain precise electronic parts and circuits, they should be installed in a place free from humidity, direct sunlight, and vibrations.

5.8 Practical Training

5.8.1 Aneroid Barometer

It is not necessary to repair at station for aneroid barometer. At this practice, open the cover and check the mechanism. Make observation of the barometer capsules, gears, lever, and hair springs (See Figure 5.3 and 5.4).

5.8.2 Aneroid Barograph

Examine the aneroid barograph to understand the mechanism for maintenance. The aneroid barograph is consists of the barometer capsule, the clock-driven drum, and the pen system. The indicator can be adjusted by rotating the pointer adjusting knob. Repair the clock-driven drum according to the repair instruction in Chapter 2: Measurement of temperature. It is recommended not to shift the pen arm, and bimetallic compensator.

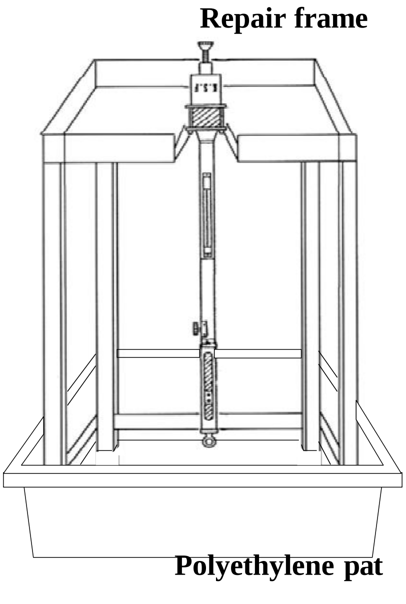
5.8.3 Disassembling and Cleaning the Mercury Barometer

(1) Preparation and precautions

This section covers the practice of disassembling and cleaning a Fortin barometer. It is ideal to clean the barometer on a fine dry day. Because, the air mass of high temperature and high humidity contains much dust. Cleaning should be performed slowly and steadily.

The barometer must be turned upside down for disassembly and cleaning work, like transporting. With the barometer standing in a vertical setting, tighten the adjusting screw (Figure 5.2 (18)) and fill the glass tube with mercury.

When the mercury comes into contact with the top of the glass tube, it emits a metallic sound like a click. This sound should be kept in mind to check for



entrance of air bubbles after cleaning.

After filling the glass tube with mercury, remove the barometer from the hanger plate and turn it upside down. Use cleaning tools free of oil, moisture and acid to prevent amalgamation.

Figure 5.10 Repair frame and Polyethylene pat

During disassembly and cleaning, it is important to remember the feeling of the tightening of the screw to reassemble the components as before.

Tools required for disassembly and cleaning are listed in the attached table.

(2) Disassembling the mercury cistern

In the same way for transporting the barometer, turn the barometer upside down after the mercury reaches the top of the glass tube. Install the barometer in the repair frame for mercury barometer (Figure 5.10). It is recommended to pack the barometer with polyethylene bag from the scale to barometer tube. Pressing the brass cylinder, turn the screw under cover (Figure 5.11, b), to the left, to remove.

Pick up the wash-leather bag to check for mercury leakage. If mercury is leaking, press the wooden base screw bridge with a finger, turn the barometer back to the vertical setting, and remove the leaking mercury into a beaker. This leakage mercury has been amalgamated and must not be mixed with mercury in the mercury cistern.

Pressing the upper part of three screws (Figure 5.11, d) with one hand, turn the brass cylinder (Figure 5.11, c) to the left to remove. If the screw is stiff, tighten it slightly, apply a small amount of oil, or pat it slightly, before loosening the screw.

Pat the wash-leather bag to remove mercury, and turn the boxwood counterclockwise (Figure 5.12) to which the wash-leather bag is attached. If the screw is stiff, tighten it with a rather thick hemp thread (Figure 5.13, a, b) and the other end around the hand (Figure 5.13, c), and turn the boxwood counterclockwise with the thread. This should be done carefully not to leakage mercury, as the glass cylinder is filled with mercury (Figure 5.12).

(3) Draining mercury from the mercury cistern

Syringe a small amount of mercury into a beaker. Be careful not to splash the mercury. Insert a finger into the mercury cistern to feel the opening of the tube (Figure 5.14,b). Plug the opening with a finger to prevent mercury flowing out of the glass tube. Excess force will break the tapered part of the glass tube. With the opening of the tube plugged with the middle finger, lift up the barometer with the other hand, and pour mercury into a beaker slowly without spilling outside the beaker. After removing the mercury completely, turn the barometer upside down as before and unplug the opening of the glass tube.

(4) Disassemble the mercury cistern glass cylinder

Loosen and remove three screws (Figure 5.15, a) one by one, feeling the tightening of the screw. Next, remove the brass metal frame, wooden frame, and glass cylinder (Figure 5.16).

It is recommended to mark the screws and holes to prevent mismatching during the reassembly. It is also recommended to mark the glass tube seam and gasket positions to prevent mercury leakage after reassembly.

The leather gaskets attached in the upper and lower parts of the glass tube should not be removed. When the gaskets are very dirty, however, remove and soften them well. Pinch the gasket with a pair of tweezers and immerse it into the beaker filled with filtered mercury to allow the mercury to adsorb the dirt. Then attach the gaskets during reassembly.

(5) Filtering mercury and cleaning components

For the filtering the mercury, pour the mercury into the strain that stands on a beaker covered by a thick paper (cross grained paper) (See Figure 5.17).

First, filter mercury with a rough strain, then again with a fine strain. Repeat this twice or more until no dust is found. Since this process requires a lot of time, this filtering work should start as soon as the mercury is drained into the beaker.

Wipe the glass cylinder with cleaning paper moistened with alcohol, being careful not to rub off the marks. Scrape off excess dirt with a cutter, taking care not to damage the glass cylinder, then polish the surface with a toothbrush and toothpaste. Wipe the glass cylinder sufficiently to remove moisture.

Wipe the boxwood part (Figure 5.16, c) with the cleaning paper. Wipe the inside of the wash-leather bag (Figure 5.12, b) with the cleaning paper. Then, put single-filtered mercury into the bag up to about 1/3, hold the bag with one hand to prevent mercury from splashing, and rub it with another hand to allow the mercury to adsorb the dirt. Repeat this process until the dirt in the bag is not found.

Filter the contaminated mercury again and repeat it until it becomes clean.

Wipe dust off the ivory pointer with a brush and the paper softly. Take care not to move or damage the ivory pointer, as it will affect index error. Wipe dust off the wooden frame and glass tube with a brush and the cleaning paper.

Some barometers contain mica plates (Figure 5.2, 22) inside the brass cylinders (Figure 5.2, 21). Remove the mica plates carefully and wipe dust off with the cleaning paper or a brush.

Bubbles often cling to the inlet of the glass tube. Pull them out by inserting a well-dried iron wire (such as a needle).

(6) Assembling the mercury cistern glass cylinder

Reassemble the glass cylinder in the reverse order of disassembly. Before reassembly, wipe dust off with clean paper or brush very carefully.

Hold the upper and lower parts of the glass tube, assemble it to the main body. Be careful not to mix up the upper and lower sides and its orientation or leave fingerprints. When the gasket comes off, soften and wash it well with mercury before setting it into the groove.

Place the boxwood (Figure 5.16) on the main body and cover it with the brass metal frame (Figure 5.16), paying careful attention to the marks and the gaskets.

Attach the three screws (Figure 5.16) to the original positions. Tighten the screws while rotating the main body and adjusting the balance of screws to each other. Unbalanced tightening may result in mercury leakage or glass tube breakage.

To clean the assembled mercury cistern (Figure 5.15), pour mercury through the clearance of the wooden base while filtering so that the mercury adsorbs dirt. To drain the mercury, plug the opening of the tube (Figure 5.15, b) with a fingertip covered with a fingerstall and turn the main body upside down. If this is done when the mercury is concave at the opening of the tube, bubbles will enter into the tube. To prevent this, heat the main body tube with a dryer to allow the mercury to expand before plugging the opening of the tube.

(7) Filling mercury

Pour filtered mercury into the mercury cistern while filtering it again with a fine strain. At this time, keep the mercury covered (Figure 5.17) to prevent dust from entering.

Mercury is concave at the opening of the tube that has been plugged with a finger. If mercury is poured while it remains concave, air bubbles will appear at the top of the glass tube when the barometer is turned back to its vertical setting. These bubbles will deteriorate the degree of vacuum. Expand the mercury by heating it with drier until it becomes convex at the opening of the tube. The convex is hardly visible from above, so you need to observe it very carefully from other angles.

When the mercury becomes convex at the opening of the tube, filter and pour mercury again until the mercury rises with surface tension just before overflowing. Add refined mercury, if required.

(8) Assembling the mercury cistern

Wipe dust off the wash-leather bag, and then secure the wooden frame tightly not to allow the rising mercury to spill. Make sure that the gaskets are properly attached inside the wooden frame.

Push the screw bridge wood of the wash-leather bag into the mercury cistern with a fingertip to make sure that mercury is not leaking from the mercury cistern glass cylinder and the wooden frame (Figure 5.12). If mercury is leaking, stop it by tightening the three screws of the brass metal frame. If mercury is still leaking, disassemble the gasket and soften it again.

When tightening the screws of the brass cylinder, take care not to break the screws. If the screw has been amalgamated due to mercury leakage, ask service personnel for repair.

Tighten the adjusting screw to complete the assembly of the glass cylinder.

At this stage, remove the polyethylene bag attached the barometer.

(9) Cleaning the graduation protective glass tube

After a long time use of a mercury barometer, the graduation protective glass tube (Figure 5.18, A) may become too dirty to read the vernier clearly. The dirty glass tube should be cleaned at the same time when the mercury cistern is checked.

To prevent the entry of bubbles, tighten the adjusting screw and turn the barometer back to a vertical setting. Loosen the adjusting screw by turning two or three turns.

Loosen the glass catch ring holding screw (Figure 5.18, a) under the graduation protective glass tube, it will go down together with the protective tube. When the latch holding screw (Figure 5.18, b) comes out of the graduation protective glass tube, remove the screw. The hanger metal fixture now will come off.

The graduation protective glass tube comes off, too. Clean the inside with paper. Dust off the graduation and vernier lightly. If there is amalgam on the graduation, the instrument should be repaired by service personnel.

After cleaning the glass tube, attach the latch holding screw. Lift up the protective tube catch ring slightly and tighten the holding screw. Assemble the glass tube with some clearance enough to rattle, allowing for expansion.

(10) Inspecting the barometer

After disassembly, cleaning, and reassembly of the barometer, check the outer tube for mercury drops. Stand the barometer upside down and leave overnight to check for mercury leakage. If mercury leakage is found, readjust the screws.

If there is no leakage, turn the barometer back to a vertical setting and inspect the degree of vacuum. It can be judged by a metallic sound like a click when mercury comes in contact with the top of the glass tube. When this sound is heard in the same way as before disassembly, the degree of vacuum is satisfactory.

If two barometers are available, compare their index errors before cleaning. Compare them again after cleaning to make sure that there is no change in the index error.

Tools for practice

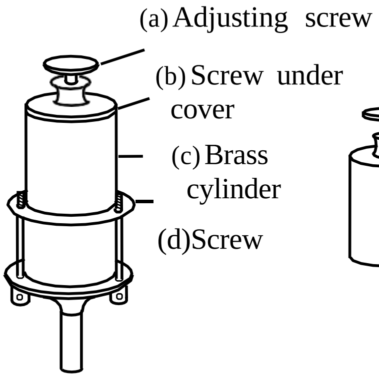


Figure 5.11 Mercury cistern

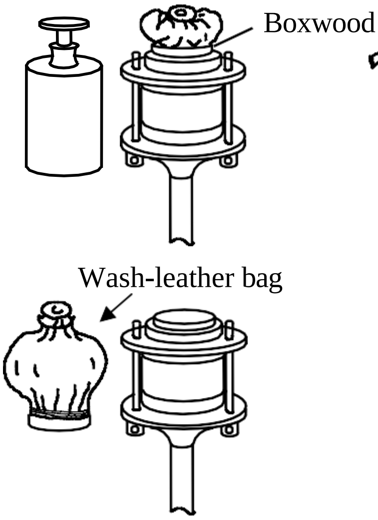


Figure 5.12 Boxwood with wash-leather bag

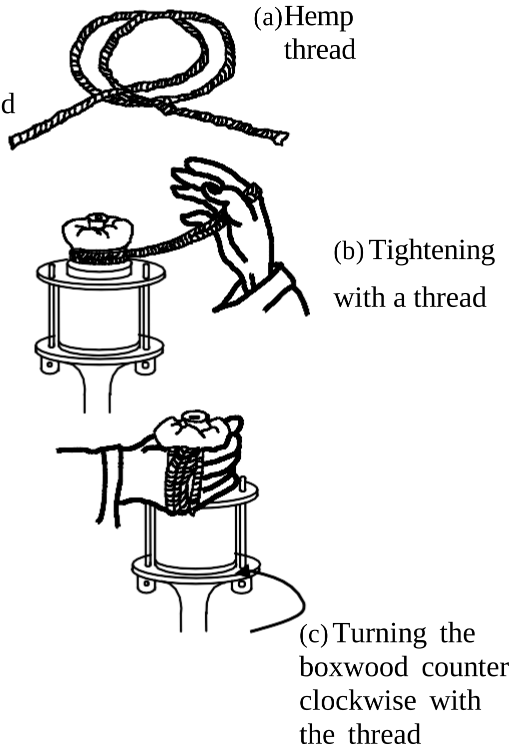


Figure 5.13 Method of turning boxwood if the screw is stiff

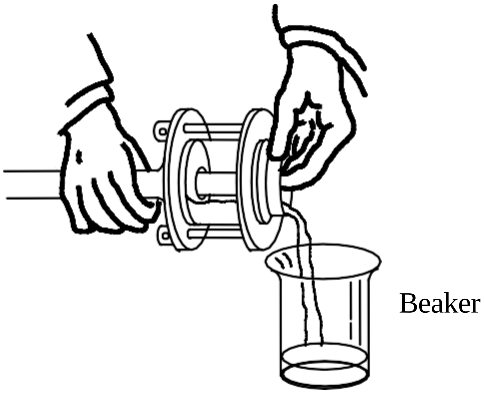


Figure 5.14 Pouring mercury into a beaker

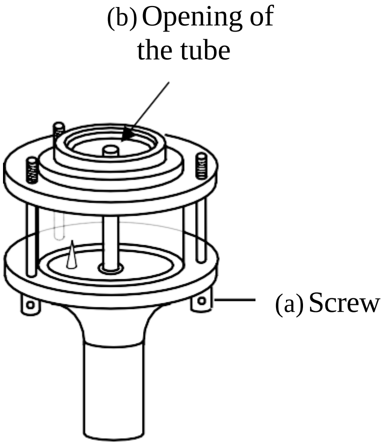


Figure 5.15 Glass cylinder

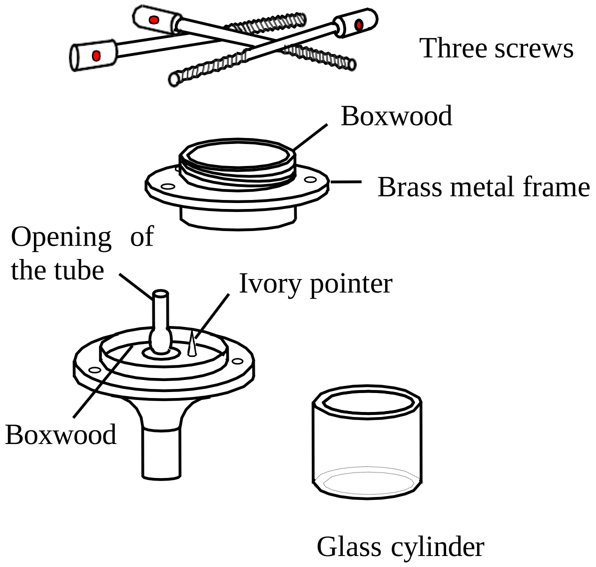


Figure 5.16 Parts of mercury cistern glass cylinder

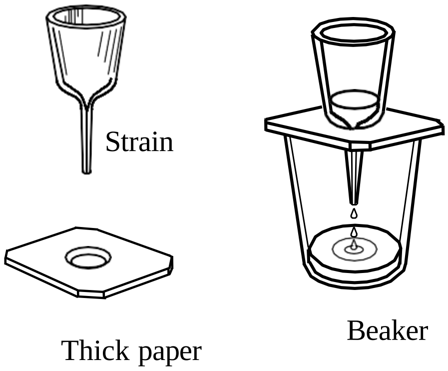


Figure 5.17 Filtering mercury

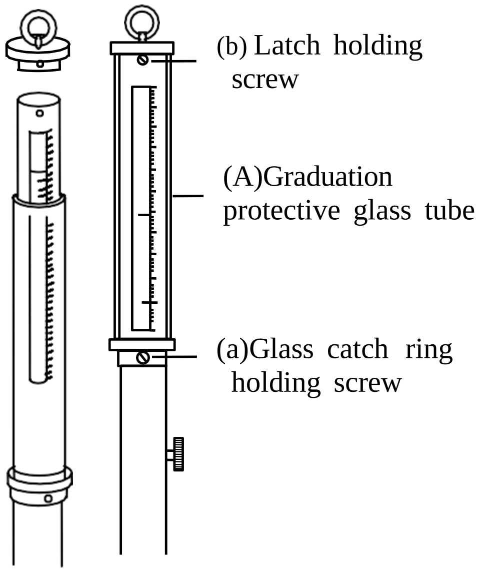


Figure 5.18 Protective glass tube

ATTACHED TABLE

Tool and supplies for disassembly and cleaning of a mercury barometer

Tools or supplies	Number of tools or supplies	Purposes

Repair frame	1 set	Set a upside-down barometer
Beaker	4	Pour mercury from a barometer
Mercury strainer	Rough and fine each one	Filter mercury of a barometer
Squirt	1	Syringe mercury into a beaker
Tweezers	A pair	Pinch the gasket
Cutter	1	Scrape off excess dirt of a glass cylinder
Drier	1	Heat a barometer tube to prevent air bubbles enter into it
Soft brush and cloth	Each one	Clean metal and glass parts of a barometer
Tool of adjusting 3-screws	1	Attach 3-screws to original positions
Dust pan	1	Pick up splashed mercury
Polyethylene pat	1	Set under the repair frame and gather leakage mercury
Well-dried Iron wire	1	Pull air bubbles out by inserting into glass tube
Alcohol	500 cc	Wipe glass cylinder with moistened paper
Toothbrush and toothpaste	1	Polish surface glass cylinder
Cleaning paper (no fluff)	100 sheets	Wipe glass cylinder, ivory pointer, etc.
Cross grained paper (thick paper)	1 sheet	Support strainer and cover beaker
Polyethylene bag	10 sheets	Store dust
Refined mercury	2 kg	Add into mercury cistern in the case of required
Leather gaskets(attached the glass cylinder)	2 sheets	Spare
Gaskets (attached the wash-leather bag)	1 sheet	Spare

Chapter 7: Standards for Meteorological Instruments

CONTENTS

Chapter 7: Standards for Meteorological Instruments

9.1 Definition of Standards for Meteorological Instruments

It is necessary to calibrate instruments prior to their deployment in order to ensure high-quality observational data. Comparison and calibration must also be performed periodically to track instrument performance and enable appropriate correction. This calibration and comparison requires a system of standard meteorological instruments. As detailed in Chapter 1, Section 1.1, there are various levels of standards, and the group of reference, transfer and working standard devices defined in the section constitutes the standard instrument system. The current chapter gives an outline of this system in Japan.

9.2 Procedures for Achieving Observation Accuracy

The accuracy of meteorological observations is evaluated comprehensively in consideration of errors caused by the performance of instruments, measurement methods and surrounding conditions.

Requirements for the accuracy of individual observations as provided in the CIMO Guide are described in Section 1.3.

To attain the required level of accuracy, it is necessary to use instruments whose performance exceeds the requirements. It is also necessary to keep instruments for comparison and calibration to enable adjustment of operational instruments for maximum performance.

9.3 System of Standard Meteorological Instruments

9.3.1 Outline of the System of Standard Meteorological Instruments

Figure 9.1 shows the concept of the system of standard meteorological instruments. National meteorological standards established by each national Meteorological Service serve as the basic standards for operational use. Some of these national standards have their own traceability to international or WMO standards, while others are established independently. National meteorological standards are regarded as references, as they are traceable to other higher standards including national ones. WMO strongly recommends periodic comparison and calibration of national meteorological standards with regional standards maintained by Regional Instrument Centers to ensure the international coherency of meteorological observations among Members.

Working standards at local calibration centers are kept traceable to national meteorological standards using transfer standards (also known as travelling standards).

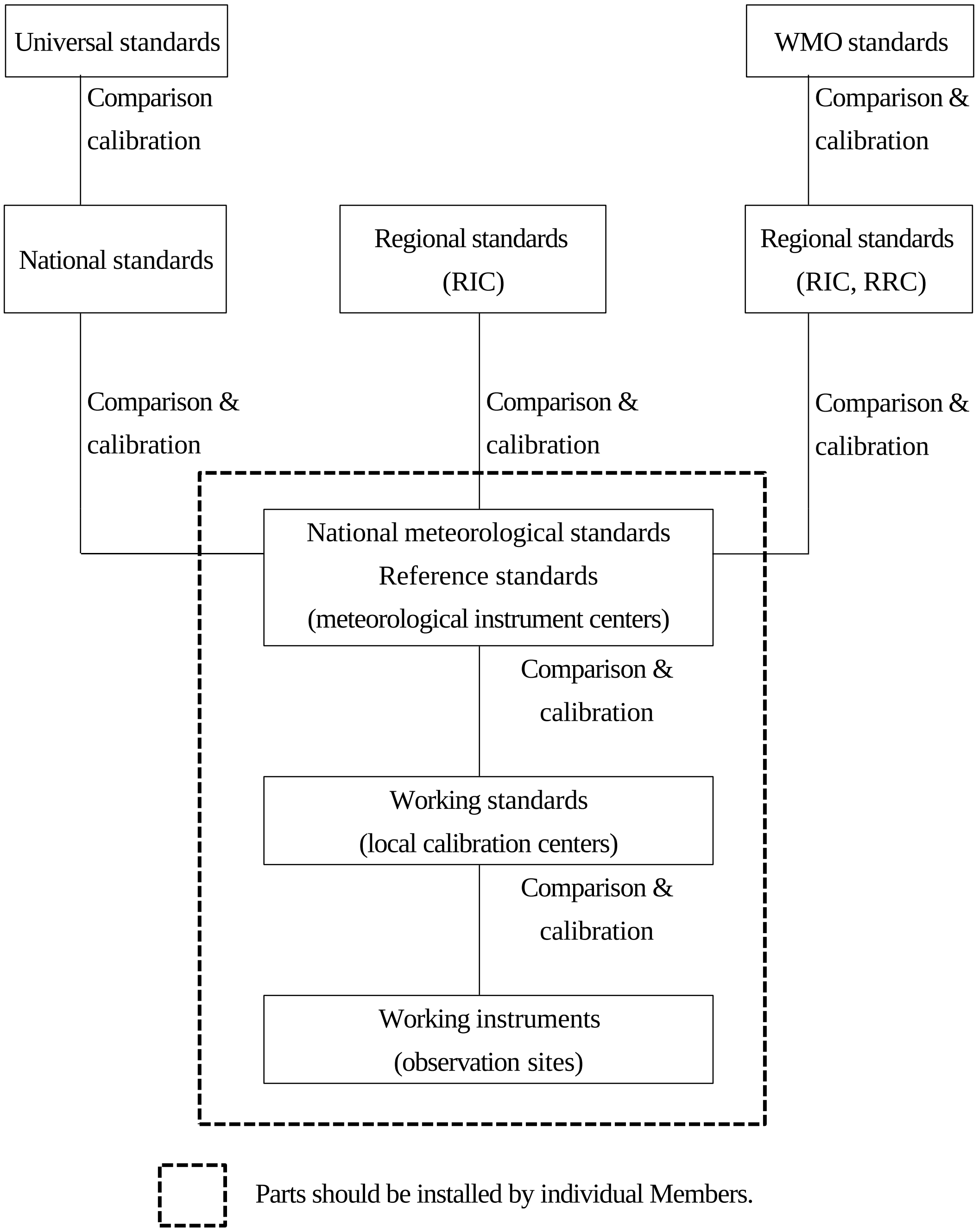


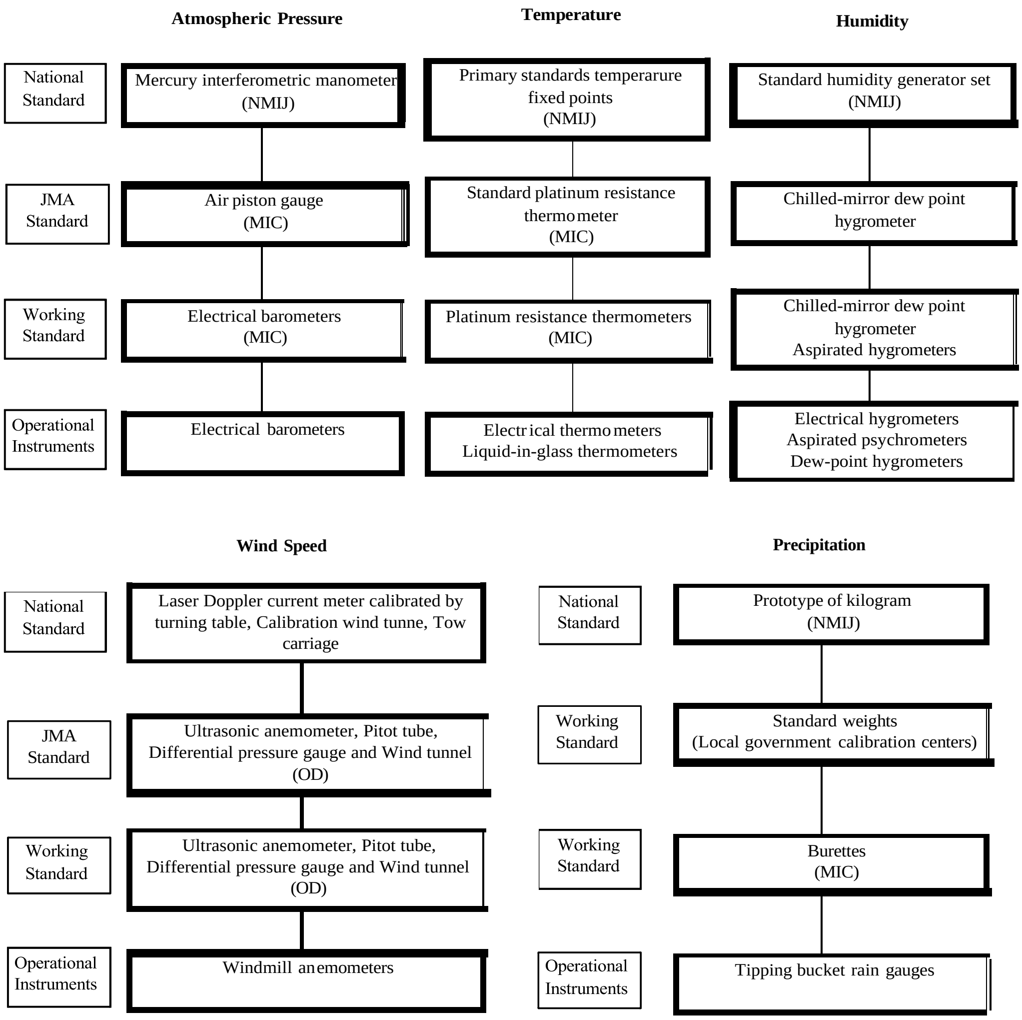
Figure 9.1 Outline of the system of standard meteorological instruments

9.3.2 Requirements for the Standard Meteorological Instrument Systems of Individual Members

Figure 9.1 shows the system of standard meteorological instruments that individual Members should establish.

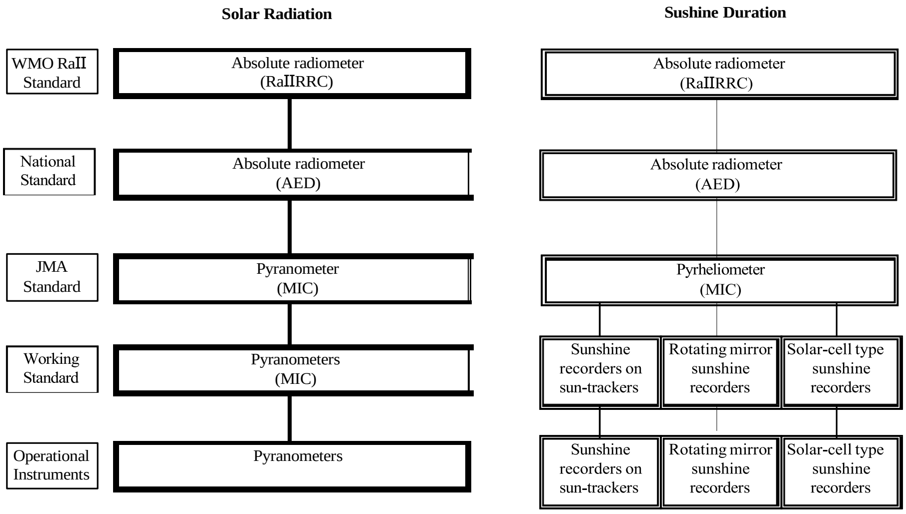
Each instrument in the system must meet the operational accuracy requirements laid down by CIMO as a minimum. Operational instruments should be corrected periodically with reference either to national meteorological standards or working standards at local calibration centers.

CIMO recommends that individual Members ask RICs for technical advice to establish their own standard instrument systems.



NMIJ: National Metrology Institute of Japan（Advanced Industrial Science and Technology）
MIC: Meteorological Instruments Center
OD: Observational Division of JMA

Figure 9.2 System of Standard Meteorological Instruments in Japan (part 1)



RRC：Regional Radiation Center AED：
Atmospheric Environment Division MIC：
Meteorological Instruyments Center

Figure 9.3 System of standard meteorological instruments in Japan (part 2)

9.3.3 The Standard Meteorological Instrument System of Japan

This section describes the standard meteorological instrument system of Japan.

Figure 9.2 and 9.3 outlines the standard system for pressure, temperature, humidity, wind speed, precipitation, solar radiation and sunshine.

JMA standards, or national meteorological standards, are maintained at the Meteorological Instruments Center (MIC), where RIC Tsukuba is also located. Working standard instruments are maintained at MIC for comparison and calibration to operational instruments.

9.3.3.1 Pressure

(1) The national standard instrument for ascertaining Japan’s primary pressure standard is a mercury interferometric manometer maintained at the National Metrology Institute of Japan (NMIJ) of the National Institute of Advanced Industrial Science and Technology (AIST). The national meteorological standard of pressure is traceable to this national standard.

(2) The national meteorological standard instrument is an air piston gauge, which also serves as the JMA standard. This JMA standard is periodically compared and calibrated with the national standard.

(3) The working standard instrument is an electrical barometer. This working standard is periodically compared and calibrated with the JMA standard at observatories.

9.3.3.2 Temperature

(1) The national standard of temperature comes from primary standard temperature fixed points at NMIJ.

(2) The JMA standard instrument is a standard platinum resistance thermometer, and is periodically compared and calibrated with the national standard. Its resistance is checked occasionally at the triple point of water at MIC.

(3) The working standard instruments are platinum resistance thermometers. They are compared and calibrated with the JMA standard at MIC.

9.3.3.3 Humidity

(1) The national standard instrument for humidity is a standard humidity generator maintained at NMIJ.

(2) The JMA standard instrument is a chilled-mirror dewpoint hygrometer combined with an electrical thermometer. The hygrometer is traceable to the national standard through periodic comparison and calibration with it. The electrical thermometer is periodically compared and calibrated with the JMA temperature standard instrument (a standard platinum resistance thermometer).

(3) The working standard instruments are a chilled-mirror dewpoint hygrometer and an aspirated psychrometer, which are periodically compared and calibrated with the JMA standard at MIC.

9.3.3.4 Wind Speed

(1) The national standard instrument is a laser Doppler current meter calibrated by turning table, a calibration wind tunnel and a tow carriage at NMIJ.

(2) The JMA standard instrumentation consists of an ultrasonic anemometer, a pitot tube, a differential pressure gauge and a wind tunnel. The first three are periodically compared and calibrated with the national standards.

(3) Working standard instrumentation consists of an ultrasonic anemometer, a pitot tube, a differential pressure gauge and a wind tunnel. The first three are periodically compared and calibrated with the JMA standard in JMA’s Observational Division.

9.3.3.5 Precipitation

(1) There is no national or JMA standard instrument for precipitation.

(2) Working standard instruments are burettes, which are periodically inspected with standard weights at local government calibration centers.

9.3.3.6 Solar Radiation

(1) Solar radiation requires traceability to the WMO standard.

(2) Regional standard instruments are maintained under WMO standards. The standard instrumentation for Region II is a group of absolute radiometers maintained at JMA’s Atmospheric Environment Division (AED). The regional standards are periodically compared and calibrated with the WMO standards.

(3) The national standard instruments are absolute radiometers maintained at JMA's AED. The national standards are periodically compared and calibrated with the regional standards.

(4) The JMA standard instrument is a pyranometer maintained at MIC. It is periodically compared and calibrated with the national standards.

(5) The working standard instruments are pyranometers maintained at MIC. They are periodically compared and calibrated with the JMA standard.

9.3.3.7 Sunshine

(1) Sunshine duration requires traceability to the WMO standard.

(2) Regional standard instruments are maintained under the WMO standards. The standard for Region II is a group of absolute radiometers maintained at JMA's Atmospheric Environment Division (AED). The regional standards are periodically compared and calibrated with the WMO standards.

(3) The national standard instruments are absolute radiometers maintained at JMA's AED. The national standards are periodically compared and calibrated with the regional standards.

(4) The JMA standard instrument is a pyrheliometer maintained at MIC. It is periodically compared and calibrated with the national standards.

(5) The working standard instruments are three pyrheliometer types: sunshine recorders on a sun-tracker, rotating-mirror sunshine recorders and solar-cell-type sunshine recorders maintained at MIC. They are periodically compared and calibrated with the JMA standard.

9.4 Maintenance of Standard Systems (Comparison, Calibration)

Instruments show secular changes in performance and correction requirements. To maintain accuracy, traceability to standards must always be kept.

9.4.1 Comparison and Calibration via Regional Instrument Centers

CIMO recommends periodic comparison and calibration between national standards and regional standards at RICs once every five years. These tasks can be performed using travelling standards.

9.4.2 Comparison and Calibration by Individual Members

CIMO recommends periodic comparison and calibration of operational instruments with national or working standards. The periodicity of such work should be determined by considering secular changes in the performance of instruments and working conditions. Instruments with significant changes over time require frequent calibration.

CIMO recommends that individual Members consult RICs for advice on the maintenance of their systems of standard instruments.

9.4.3 Instruments Used for Comparison and Calibration

The accuracy of national meteorological standards and working standards must be of an equivalent or higher level than that provided by CIMO.

As it is difficult to carry out comparison and calibration with high accuracy in the open air (where atmospheric conditions may change more quickly than instruments can respond to them), calibration chambers in which temperature, humidity and pressure can be stably maintained are used for these tasks. Calibration chambers maintained by JMA are described in Section 9.4.5.

CIMO also recommends the use of travelling standards for comparison between reference standards and working standards. Travelling standard equipment must be rigid enough to endure transportation, and be stable enough that its performance does not change after transportation.

9.4.4 Standard Instruments Used for Comparison and Calibration in Japan

This section introduces the reference standard instruments for pressure, temperature and humidity maintained at RIC Tsukuba.

9.4.4.1 Pressure

(1) Air piston gauge

This air piston gauge consists of a piston gauge, a vacuum gauge, a vacuum pump, a pressure adjuster and a pressure medium (dry air) (Figure 9.4 and Picture 9.1).

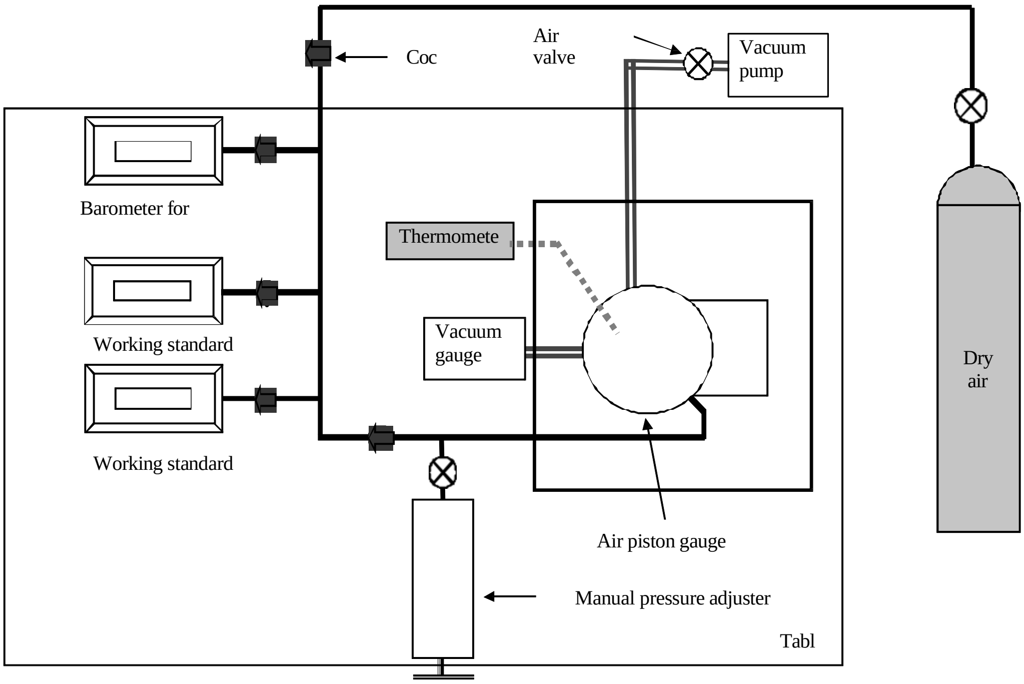


Figure 9.4 Air piston gauge system overview

Picture 9.1 Air piston gauge

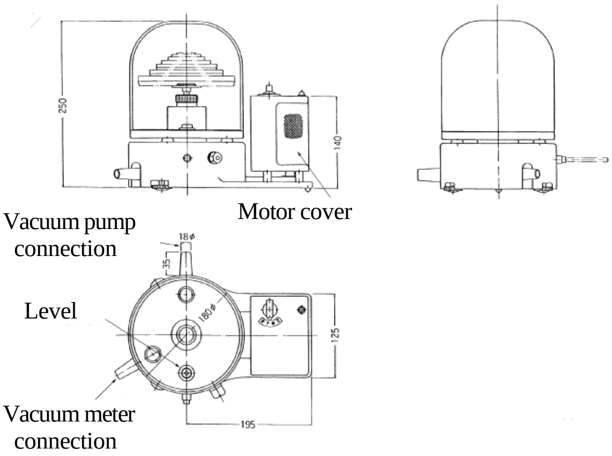


Figure 9.5 Air piston gauge

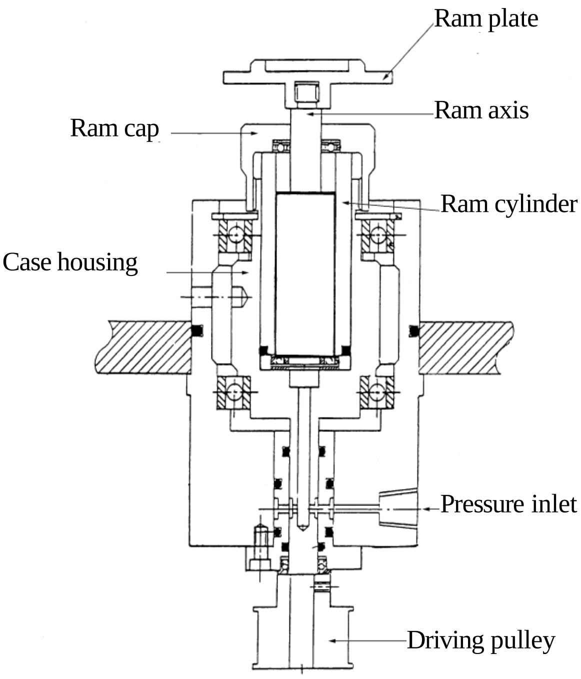


Figure 9.6 Ram cylinder

It produces an accurate level of pressure by balancing the vacuum section (the upper part) and the constant-pressure section (the lower part). Pressure in the lower section is determined by placing an approved high-accuracy weight on the upper section. By combining several weights, a wide range of pressures from 50 hPa to 1,150 hPa can be covered at intervals of 10 hPa.

Pressure in the lower section is adjusted with the vacuum pump and pressure adjuster so that it balances with the weight on the upper section.

The pressure in the lower section is led to the air inlet of the pressure gauge to be calibrated through the piping cock.

Figure 9.5 shows an overall view of the air piston gauge. Figure 9.6 is a sectional view of the rotary mechanism that produces the vacuum in the upper section and pressure in the lower section, both of which are in the ram cylinder. The two sections are separated and kept airtight by the smoothly rotating ram axis.

On top of the ram cylinder is a ram dish, on which high-accuracy weights are placed. Dry air (the pressure medium) is introduced into the lower section to create pressure, whose level can be controlled accurately by changing the weights.

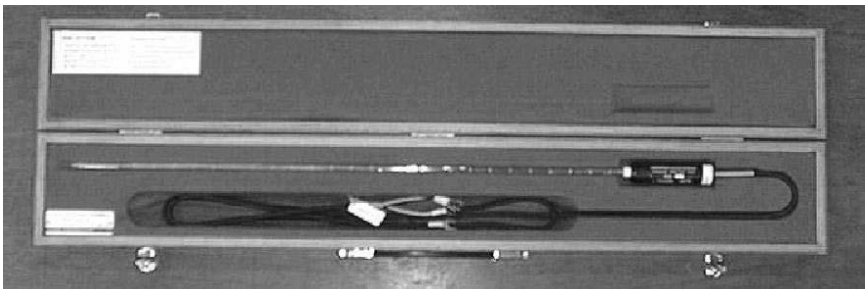
The weights are made of stainless steel and are approved by comparison with standard weights.

9.4.4.2 Temperature

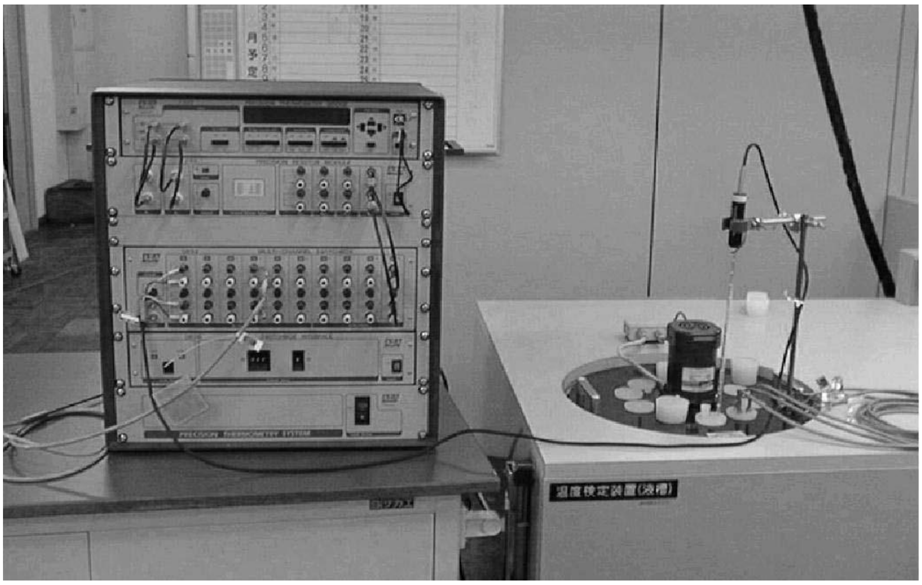
The national meteorological standard instrument for temperature is a standard platinum resistance thermometer. Its principles of measurement are described in Chapter 2 Measurement of Temperature.

This type is also used as a travelling standard.

Picture 9.2 shows the sensor of the standard platinum resistance thermometer, and Picture 9.3 shows calibration with this type of thermometer in a liquid-type calibration chamber. The sensor of the standard thermometer is placed at the center of the calibration chamber, and the thermometers to be calibrated are set around it. Each sensor is connected to an alternating-current bridge through a switch box to allow measurement of its electrical resistance. The resistance levels of each sensor are measured one by one for calibration of the temperature scale against the standard.



Picture 9.2 Standard platinum resistance thermometer sensor



Picture 9.3 Thermometer calibration system

9.4.4.3 Humidity

The humidity standard setup consists of a chilled-mirror dewpoint hygrometer and an electric thermometer. The electric thermometer is identical to that described in the previous section, and the chilled-mirror dewpoint hygrometer is described in this section. Figure 9.7 shows its configuration.

A chilled-mirror dewpoint hygrometer accurately determines the quantity of moisture in the air by directly measuring the dewpoint or frost-point temperature. Figure 9.8 shows the principle of its measurement. The sensor consists of a metal mirror, which is cooled until dew forms on its surface.

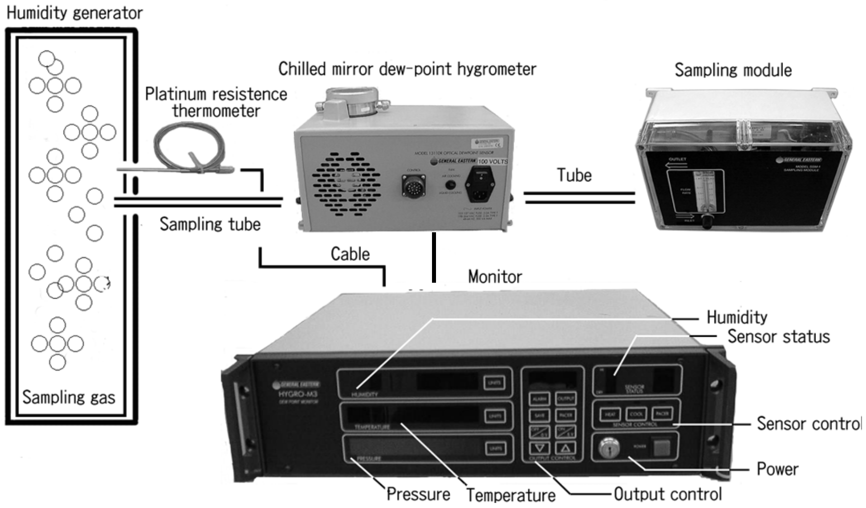


Figure 9.7 Chilled-mirror dewpoint hygrometer configuration

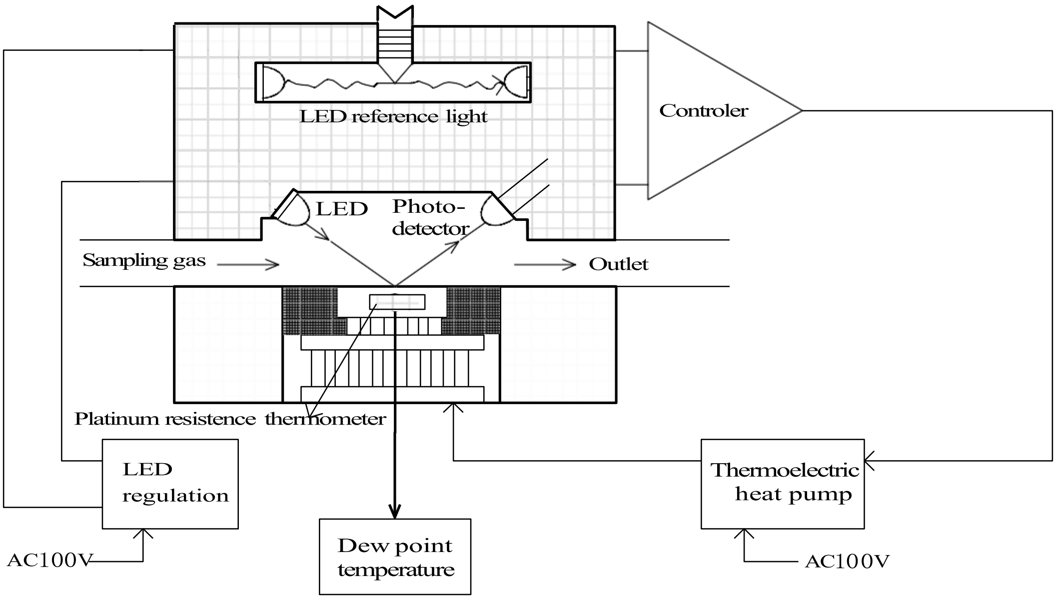


Figure 9.8 Principle of measurement of a chilled-mirror dewpoint hygrometer

Dew formation is determined optically; when it begins to appear, the temperature (known as the dewpoint temperature) of the mirror is measured with the electric thermometer.

The chilled-mirror dewpoint hygrometer shown in Figure 9.7 measures a range of humidity levels from 0.03% to 100% with a sensitivity of 0.03°C for dewpoint temperature.

9.4.5 Facilities Used for Comparison and Calibration

This section introduces the inspection facilities (calibration chambers) maintained at RIC Tsukuba. The calibration facilities consist of the six units described below.

(1) Temperature calibration chamber (air type)

This is an air chamber whose internal temperature can be set to a value between -40°C and +50°C with an accuracy of ±0.3°C and a stability of ±0.3°C/min. It is used to compare and calibrate thermometer equipment such as bimetal thermographs whose sensors and recorders are integrated and cannot be separated.

(2) Temperature calibration chamber (liquid type)

This is a liquid chamber whose internal temperature can be set to a value between -85°C and +50°C with an accuracy of ±0.1°C and a stability of ±0.1°C/min. It is used to compare and calibrate the sensors of thermometer equipment such as electrical thermometers whose sensors and recorders can be separated. The chamber is filled with a special inert liquid that makes it possible to achieve a temperature of -85°C.

(3) Thermal shock test chamber

The internal temperature in this type of chamber can be raised from -40°C to +50°C within 30 minutes with an accuracy of ±1.0°C, and change from high to low temperatures is also possible. It is used to test the durability of instruments against cyclic temperature changes.

(4) Pressure calibration chamber

The pressure in the chamber can be set to a value between 1,050 hPa and 4 hPa with an accuracy of ±1 hPa. It is used to compare and calibrate barographs and barometer probes.

(5) Two-pressure humidity generator

This chamber generates specific levels of humidity based on the principle that humidity (the quantity of water vapor in a particular volume of gas) is proportional to pressure when the temperature is constant. The pressure in the chamber can be reduced by adjusting the expansion valve to lower the level of humidity in proportion with pressure. Although the chamber cannot form a specific level of humidity in conditions of temperature change, it provides sufficient space for comparison and calibration of large integrated instruments whose sensors and recorders cannot be separated, such as hair hygrographs.

The generator can produce levels of relative humidity between 15% and 95% with an accuracy of ±1%.

(6) Thermo-hygro regulator (wet and dry air mixing type)

This regulator generates specific levels of humidity by mixing saturated air (i.e., that with a relative humidity of 100%) with dry air. The method allows temperature control and consequently the attainment of specific levels of humidity at specific temperatures. It can produce levels of relative humidity between 20% and 95% (accuracy: ±2%) with temperature control between -40°C and +50°C (accuracy: ±0.5°C), and can be used for purposes such as testing the temperature characteristics of hygrometers. As the space in the chamber is limited, it cannot be used to compare and calibrate large instruments whose sensors and recorders cannot be separated, such as hair hygrographs.

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