TEMPERATURE: TECHNIQUES AND INSTRUMENTATION

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Summary

Accurate measurement of temperature is critical to all measurements in science and technology. Temperature is based on thermodynamic concepts. Fundamental equations are used to define temperature. The current International Temperature Scale (ITS-90) is based on thermodynamic invariant points, instruments for interpolating between fixed points, and interpolating equations. Standards laboratories around the world calibrate many kinds of practical thermometers for use traceable to the ITS-90. These include electrical resistance methods, radiant energy methods, thermocouples, and liquid-in-glass thermometers. The principles of measurement and use are presented here. Brief discussions of calibration methods and common errors are included.

1. Introduction

All of us are already familiar with the concept of temperature based on our own bodies. The nerve endings below our skin serve as the temperature sensor and identify if we are hot or cold. The nerves relay the sensing message to our brains, and our brains serve as the measuring instrument to convert that sensing to temperature. This is the way more sophisticated instruments work, with a sensor, a relaying method, and an instrument to convert the sensor signal to a temperature measurement.

All of us have also used a thermometer to tell us how hot, or how cold, something is. We measure temperature in degrees, referring to the scale in common use in our society. For most of the world this is in degrees Celsius (formerly centigrade) or in Kelvins. In the United States the common scale is degrees Fahrenheit. The concept of temperature, its measurement, and the scales we use, have changed dramatically in the last century and are still changing. Although quite sophisticated now, improvements in concepts, devices to measure temperature (thermometers), calibration systems, and the accuracy

and precision of measurement are still being improved and refined. All aspects of temperature measurement are subject to changes by international agreement through the International Committee on Weights and Measures. Because scientists around the world must agree on the definition and interpretation of temperature there is a political element to those agreements. However, the science of temperature measurement has reached a high degree of accuracy and precision.

1.1. The Importance of Temperature Measurements

The ability to measure temperature accurately is a critical requirement for earth energy balances and to the understanding of macrosystems, for an understanding of global warming, and for successful scientific analysis. Accurate temperature measurement is critical to all chemical and physical scientific research. The latter includes life systems of all kinds, global heating and cooling processes, weather, and oceanography. Any analysis that includes energy exchange must have precise and accurate temperature measurement to be successful. In many cases an error in temperature measurement is so important that all other measurements need not be known as well. It is often the most critical of the parameters being measured because the thermodynamics of equilibria and the kinetics of processes usually depend exponentially on temperature.

1.1.1. What is Temperature?

Temperature is the level of thermal energy. Thermal energy transfer only occurs spontaneously from a high temperature to a low temperature, never the reverse. So temperature is the driving force for heat transfer. The concept of temperature is theoretical, and based on fundamental physical relationships. The basis of temperature scales is, historically, the perfect gas interpretation of the thermodynamic temperature scale.

If we have a scale representing temperature from a low temperature to a high temperature, and use the spacing of the steps of the scale based on equal units of energy, then we have a temperature scale. To go from some step on the scale to the next lower step we must remove one increment of energy. The amount of energy to go from one step to the next will depend on the size of the step and the material containing the thermal energy. In principle it is possible to define temperature as the level of thermal energy, if we specify what medium we use to contain the thermal energy. And for a linear scale, we must specify a medium we can accept that has a direct proportionality constant between energy and temperature. Historically, Lord Kelvin (1824–1907) proposed the medium for the thermodynamic temperature scale to be a perfect gas, one that obeys the relationship, per mole:

$$PV = RT \tag{1}$$

The pressure–volume product (PV) equals the internal energy in a mole of perfect gas, and R is the proportionality constant—the universal gas constant. T is absolute temperature. Reducing the temperature one step on the scale changes the energy of the gas and removes the energy corresponding to that step on the scale. Kelvin used the Carnot cycle as the mechanism of adding or removing energy, without wasting any

energy through turbulence or other friction. Units for energy and temperature are arbitrary. The proportionality constant (R) is accepted as a fundamental physical constant; but its value depends on the units in use, accepted over a long time, as fundamental scientific units. The basis for all temperature measurement, then, is thermodynamic temperature, based on fundamental physical relationships. Temperature, then, is a fundamental physical quality. It is the most difficult of the fundamental physical quantities to define and measure.

1.2. Fundamental Relationships

Because of the limitations inherent in gas thermometry measurements, other fundamental relationships are essential to establish a scale that approaches thermodynamic temperatures. For example, both acoustic thermometry and noise thermometry were useful at low temperatures to supplement gas thermometry. The upper limit of gas thermometry would have been the upper limit to ITS-90, if Planck's law of spectral radiation, another fundamental relationship, had not been used above the gold point.

All of the fundamental relationships depend on fundamental physical constants, such as Avogadro's number, Planck's constant, and the Boltzmann constant. The accuracy of these fundamental constants is a limitation on the accuracy of temperatures based on them. However, the basis for all temperature measurements is the thermodynamic temperature scale, which is implemented through these fundamental relationships. According to Eq. (1) the energy contained in the gas will be zero if the temperature goes to zero. Mathematically, we have the concept of an absolute zero of temperature, conforming to zero thermal energy in a perfect gas. This is the basis for the thermodynamic temperature scale proposed by Kelvin. In honor of Lord Kelvin the steps on the scale are designated as K. In principle, temperatures can be measured, counting the units of K from absolute zero to the highest possible temperature. For practical reasons we also use the Celsius scale because it is more comfortable to the public. It has its zero at 273.15 K.

1.3. General Philosophy of Temperature Measurement

As explained above the definition of the thermodynamic temperature scale is a theoretical one, using equal increments of energy to define the scale. The perfect gas law was the original basis for the scale, based on experimental data for real, monatomic gases at low pressure. The concept of absolute zero and the absolute temperature scale came from that early research. The perfect gas law is a fundamental law. That is, it is one that relates energy of a perfect gas—through a fundamental physical constant—to temperature. Thermal energy is related to temperature in a fundamental way. However, gas thermometry requires a complex series of measurements because perfect gas behavior is achieved as the concentration of real gases approaches zero. A gas thermometer is large, and must be held in a large isothermal environment while a series of measurements are made. The only practical way to achieve an isothermal environment for a long time is to select temperatures corresponding to phase changes— such as the ice point—that remain at constant temperature as long as the phase mixture is maintained (thermodynamic invariant points). Choosing two such fixed points, a

series of measurements with, for example, a constant volume gas thermometer, can be made at a series of decreasing gas concentrations at each fixed point to obtain the limiting value of the PV product at each fixed point. Then the same procedure can be used at intermediate temperatures between the two fixed points. This is so difficult and time-consuming that it is not practical for routine use. Precise measurements of this nature can be used to calibrate more practical instruments, to serve as the representation of thermodynamic temperatures, achieved by gas thermometry.

Kelvin originally recommended using the ice point to steam point interval, divided into 100 parts to establish the size of the degree, now identified as the Kelvin. He recommended that those two points be the basis for the scale because they were the most precisely known fixed points at that time; but he preferred a single, accurate point of highest precision to define the scale. Any adjustment of the defining point would then affect all other points and facilitate easy conversion to the new, better-defined scale. The original 1927 International Temperature Scale was based on steam point/ice point interval, although the steam point was recognized as more uncertain than the ice point. In 1948 the triple point of water was adopted as the defining point and defined as 0.01 °C, relating it to the ice point, but recognizing it as being more precise than the ice point. When the Kelvin scale was adopted as the fundamental scale the triple point of water was fixed at 273.16 K. All subsequent scales must pass through this point. In practice, other invariant points are also needed.

The International Temperature Scale, presented below, is based on primary fixed points, to define the scale, and utilizing secondary fixed points, with the instrument for interpolation between fixed points specified, so that the scale can be realized by all scientists. The primary points are known more accurately than the secondary points.

Using a single point to define a scale actually requires two points, zero and 273.16 K. Since zero K has never been achieved the scale can be established in theory, but not in practice. Over the last seven or eight decades the International Temperature Scale has been adjusted to more nearly approximate the theoretical thermodynamic temperature scale. This has been an evolutionary process conducted primarily in standards laboratories of various countries around the world. The research has been extremely difficult, requiring sophisticated measurements and superior physics.

By defining fixed points by gas thermometry, and by interpolating the intermediate temperatures using gas thermometry to calibrate working instruments for interpolating between fixed points, a sophisticated national standards laboratory can estimate true thermodynamic temperatures with great precision. However, the process is so difficult that comparisons between laboratories have aided in establishing working standards that come most closely to the true thermodynamic scale. The process of achieving that scale with precision is called realization of the scale.

No single instrument can be used to measure the full range of temperatures. The 1927 scale was based on three instruments: the platinum-resistance thermometer, the type S thermocouple, and the optical pyrometer. The interpolating equations were selected to pass through the defining points; but two different equations were needed for the low and moderate temperature ranges of the resistance thermometer. The ITS-90 has 17

defining points, one of which is the triple point of water, which is taken as exact at 273.16 K. The scale is subdivided into 14 ranges or subranges, with defining equations for each and with alternative measurement instruments in some ranges. Ranges overlap, and the first derivatives of the interpolating equations are as continuous as possible. Slightly different values can be obtained for a temperature in overlapping ranges using the same instrument but with different interpolating equations (because of selection of different equations and fixed points for calibration). However, the deviation of the equations from true thermodynamic temperature is believed to be of millikelvin (mK) magnitude. The net result is a scale that can be achieved in standards laboratories, calibrating each instrument to pass through the fixed points. The latest version of the International Temperature Scale was adopted in 1990 (ITS-90). This, too, is impractical for most applications, so secondary instruments are used in practice, with their calibration traceable to the thermodynamic scale.

1.4. Precision and Accuracy

Any variable that depends on temperature in a nonredundant way can be used to measure temperature. Such measurements are useful only if both the precision and the accuracy of the measurement are known. Precision is represented by the statistical measurement of the variable. With many replications a statistical representation of the measurement will give the mean and the standard deviation, to set limits on the confidence with which the variable has been measured. A measurement may be very precise, but inaccurate.

Accuracy is the confidence that the variable measured represents the thermodynamic temperature as represented by ITS-90, the latest version of that approximation. This can only be estimated by understanding the deviations of ITS-90 from thermodynamic temperature (believed to be negligible), plus all the other deviations in the correlation of the variable to ITS-90. The latter are very important and can be enormous. Sources of those deviations include:

- errors in the function relating the variable to temperature (errors in secondary calibration of the working instrument);
- errors in the function used in the measuring instrumentation to represent the measuring function (e.g., the instrument may use piece-wire linear equations to represent a polynomial that represents the measuring variable relationship to temperature);
- errors in the absolute value of the variable, producing an offset from the true value of the variable and an effect in temperature;
- errors in installation of the sensing device or the measuring instrument; and
- deterioration of the measuring instrument or the sensing device.

Commercial instruments usually are calibrated to represent precision, not accuracy. It is not unusual for a commercial instrument to indicate temperature to 0.01 °C, but to be accurate to poorer than ± 10°C. Improper installation often occurs. It is very important for a user to understand the entire measuring device, including the sensor, the data processing system, the instrument used to measure the variable, the calibration of that instrument, the accuracy of the variable/temperature relationship, the requirements for

sensor installation, and the mechanisms of failure. Failure to do so will result in erroneous data and erroneous conclusions.

2. The International Temperature Scale

2.1. History

Cooperation between national laboratories before and after the First World War through the International Committee on Weights and Measurements culminated in the first version of the international temperature scale in 1927. This established the method of describing the scale that continues to be used, although important revisions have occurred since. The method is based on the following three requirements:

1.   *Fixed points.* These are reproducible temperatures based on thermodynamic invariant points, such as boiling points, freezing points, and triple points. With pure materials these fixed points can be produced in any laboratory and are assigned temperatures based on the thermodynamic temperature scale. Certain highly accurate fixed points are selected as defining points. Less accurate, secondary points are given to lesser significant figures for convenience in applications.
2.   Instruments that are to be used to interpolate temperatures in the intervals between fixed points.
3.   The equations to be used with the appropriate instrument to interpolate between the fixed points. These equations pass through the defining points.

The first international temperature scale (in 1927) specified four temperature ranges:
*   *Range I.* Oxygen point to the ice point; using the platinum-resistance thermometer.
*   *Range II.* Ice point to the aluminum point; using the platinum-resistance thermometer.
*   *Range III.* Aluminum point to the gold point; using the platinum 10% rhodium thermocouple.
*   *Range IV.* Above the gold point; using the optical pyrometer.

Different equations relating platinum resistance to temperature were used to interpolate in ranges I and II.

Major revisions were made in 1948, 1968, and 1990. The original scale was based on the ice point, 0 °C, and the boiling point, 100 °C, for water; establishing the centigrade scale as the primary scale.

The size of degree was 1/100 of the ice point/boiling point interval.

In 1954 the triple point of water and absolute zero were used to define thermodynamic temperature, replacing the ice point and the steam point. In 1968 the scale was extended upward and downward, and was called the International Practical Temperature Scale (IPTS). The word "Practical" served to recognize the difference between the IPTS of 1968 and ideal thermodynamic temperatures.

The relationship between centigrade temperatures (t) and thermodynamic temperatures (T) was clarified:

> The unit of fundamental physical quality known as the thermodynamic temperature, symbol T, is the Kelvin, symbol K, defined as 1/273.16 of the thermodynamic temperature of the triple point of water.
>
> For historic reasons, connected with the way temperature scales were originally defined, it is common practice to express temperature in terms of a thermal state 0.01 Kelvin lower than the triple point of water. A thermodynamic temperature expressed in this way is known as Celsius temperature, symbol t, defined by
>
> t = T – 273.15K.
>
> The IPTS uses both International Practical Kelvin Temperatures, symbol T_{68}, and International Practical Celsius Temperatures, symbol t_{68}. The relationship between T_{68} and t_{68} is the same as between T and t; in other words,
>
> $t_{68} = T_{68} – 273.15K$.(H. Preston-Thomas (1975) The International Practical Temperature of 1968, Amended Edition of 1975 *Metrologia* **12**. 7-17)

Note that defining in terms of the thermodynamic temperature scale based on the triple point of water, which can be measured more precisely than the ice point, means the traditional centigrade scale no longer has exactly 100° between the ice point and the steam point. This, and to honor Anders Celsius (1701–1744), was the reason for establishing the Celsius scale for ordinary temperature measurements instead of the centigrade scale. The scientific community has been slow to adopt the new terminology.

Many new secondary points of improved precision were added for user convenience. Temperatures above the gold point in range IV were defined by the ratio of the Planck's law intensity to the Planck's law intensity at the gold point, but no particular radiation instrument or wavelength was specified.

The IPTS-68 was amended in 1975, especially in the cryogenic temperature region where major improvements in measurement had been achieved. Low-temperature interpolating instruments included magnetic thermometers and improved gas thermometers.

The International Temperature Scale of 1990 (ITS-90) was adopted by the General Conference on Weights and Measures. This is a return to the original 1927 concept, dropping the word "Practical" because the scientific standards community believes the International Temperature Scale of 1990 represents true thermodynamic temperatures sufficiently accurately to make the distinction unnecessary.

The International Temperature Scale is intended to represent thermodynamic temperatures, and is established by the International Bureau of Weights and Measures through its Consultative Committee on Thermometry. Members of that committee are authorities from around the world on temperature measurement, many of them from national standards laboratories, such as the National Institute for Standards and Technology (NIST) in the United States. The scale is the result of many cooperative measurements, often using round-robin experiments to improve and understand methods, and interpolation schemes. It is believed to be as close as possible to thermodynamic

temperatures. However, there is a political component to the discussions. Persuasive scientists have sometimes, in the past, convinced the standards community of a detail that later proved to be not as accurate as one of the alternatives. At the present time the International Temperature Scale is believed to be so close to thermodynamic temperatures that errors of this nature are not important. Most scientists and engineers are much more concerned with transfer of the scale to their own laboratories, and the utilization of practical instruments. They need not be concerned with ITS accuracy because the errors in those processes are much greater than the errors in establishing ITS-90.

The utilization of ITS-90 requires definition, realization, transfer, and utilization. Definition and realization are provided by ITS-90, as amended; but it is not practical to use the instruments specified in ITS-90 for most applications. Then the ITS-90 is transferred to other, practical, instruments, often in a standards laboratory. These serve as working standards for similar instruments or even for different instruments. These are often sold as instruments whose calibration is "traceable" to a recognized standards laboratory, such as NIST. Utilization of the secondary or tertiary instruments requires not only calibration against appropriate standards, but installation in such a way as not to introduce errors from the heat-transfer environment, nor cause errors from operating components or conditions, and maintenance. Most errors of temperature measurement arise in the utilization of practical instruments.

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Biographical Sketch

Thomas Donald McGee is Professor of Materials Science and Engineering at Iowa State University, Ames, USA. He obtained a B.Sc. in Ceramic Engineering, 1948; B.Sc. in Mechanical Engineering, 1948; M.Sc. in Industrial Engineering, 1958, and Ph.D. in Ceramic Engineering and Metallurgy, 1961—all from Iowa State University. His has undertaken research in the Biomedical Engineering program and he is a collaborator in the Veterinary Clinical Science Department. His teaching in high-temperature processing and property measurements at high temperatures led to his interest in temperature measurement.

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His publications include *Principles and Methods of Temperature Measurement* (1988), and over 100 refereed publications and 10 patents in the following areas: high-temperature refractories, engineering education, glass science and technology, fracture of brittle materials, temperature measurement and energy control, and biomaterials. His current research is in orthopedic antibiotics, bone grafting, cements, and induced bone regeneration.