Practical Temperature Measurement

Peter R. N. Childs

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This book is dedicated to Fiona

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Preface

Temperature is both a thermodynamic property and a fundamental unit of measurement. Its measurement is critical to many aspects of human activity from the thermodynamic improvement of heat engines to process control and health applications. Current estimates of the value of the temperature measurement market run at approximately 80% of the sensor market. The range of methods and devices available for temperature measurement are extensive. Options include invasive or contact methods such as thermocouples and resistance thermometers to non-invasive techniques using, for example, infrared detectors. In addition, recent developments in optical methods and micro-manufacturing have resulted in the wider spread availability and use of advanced techniques such as coherent anti-Stokes Raman scattering and thin-film transducers for temperature measurement. The aims of this text are to introduce the concepts of temperature and its measurement, to describe the range of techniques and specific devices available for temperature measurement and to provide guidance for the selection of a particular method for a given application.

The concept of temperature, its definition and practical modelling are described in Chapter 1. Both the thermodynamic temperature scale and the International Temperature Scale of 1990 are considered. General considerations of temperature measurement are explored in Chapter 2 including thermal disturbance effects for both solids and fluids. Consideration is given to steady-state measurements and transient measurements with quantification of time response and phase lag. Critical to measurement of temperature is calibration as this provides the quantitative validation for the uncertainty of a measurement. An indication of a temperature can be worthless without information on the calibration. Methods of calibration are introduced in Chapter 2 and also in subsequent chapters where specific methods and sensors are described. Related to calibration and quantification of uncertainty is the concept of traceability, which describes the management of undertaking temperature measurement, and this is also introduced in Chapter 2.

Practical methods of temperature measurement are introduced in Chapters 3–10. For convenience the methods are categorized according to the degree of contact between the medium of interest and the measurement device. In Chapters 3–7 details of invasive measurement methods where the transducer is in direct contact with the medium such as a thermocouple embedded in a surface are given. In Chapter 8 methods where, say, a surface is treated to facilitate the temperature measurement but observed remotely are considered. An example is the use of thermochromic liquid crystals that change colour with temperature. Methods where the undisturbed medium is observed remotely are described in Chapters 9 and 10.

The range of techniques and sensors available for temperature measurement is extensive. Developments in the areas of micro-manufacture, laser technology and data processing have resulted in an increase and wider availability of measurement techniques. Consequently, where measurements might once have been made with one technology another may now be more appropriate. Chapter 11 provides a guide for the appropriate selection of measurement technique based on the demands of range, uncertainty, sensitivity, life, size, cost, manufacturing constraints, dynamic response, temperature of operation and robustness.

Related to the measurement of temperature is the measurement of heat flux. Heat flux measurement is used in the field of fluid mechanics and heat transfer to quantify the transfer of heat within systems. Several techniques are in common use, including: differential temperature sensors such as thermopile, layered resistance temperature devices or thermocouples and Gardon gauges; calorimetric methods involving a heat balance analysis and transient monitoring of a representative temperature, using, for example, thin-film temperature transducers or temperature-sensitive liquid crystals; energy supply or removal methods using a heater to generate a thermal balance; and finally by measurement of mass transfer which can be linked to heat transfer using the analogy between heat and mass transfer. The various types of heat flux sensors available as well as unique designs for specific applications are described in Chapter 12.

The framework adopted for this text involves description and definition of the physical phenomena involved prior to descriptions of temperature measurement methods and specific sensors. This allows a meaningful appreciation of the method of measurement to be developed and as a result a deeper understanding of its strengths and weaknesses. Descriptions of sensors are accompanied by schematic diagrams, photographs and circuit diagrams thereby facilitating visualisation and practical usage. Nomenclature has been defined both within the text and at the end of each chapter.

This book will be of value to engineering and physics undergraduates studying modules on instrumentation and process control and for practical project work requiring an understanding of temperature measurement methods. Specific undergraduate modules for which this book has applications include Measurement and Instrumentation, Sensors, Mechanical Measurement Technology, Testing and Instrumentation and Process Control. For postgraduates and industrialists faced with the task of selecting a particular measurement method or sensor for an experiment, product or process this text provides both thorough descriptions of the various techniques and guidance for their selection.

In writing this book advice and assistance from a number of sources has been given. I would like to express my gratitude to a former doctorate student Joanne Greenwood for her diligence and enthusiasm in her work on thin-film sensors. The background reading for this research resulted in a number of review papers, which were useful in the preparation of this book. I would also like to thank my colleagues Christopher Long, for providing encouragement at the right time, Alan Turner for his continuing inspiration as a practical engineer and Val Orringe for typing some of the tables. Finally I would like to thank the Editor, Matthew Flynn, for knowing when to accept excuses on delays and when to push!

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1 Temperature

The aims of this chapter are to introduce the subject of temperature and its measurement. Qualitative and quantitative definitions of temperature are given in Section 1.1 prior to the development of temperature scales in Section 1.2. An overview of measurement considerations is provided in Section 1.3 along with a brief introduction to the techniques available for the measurement of temperature.

1.1 Definition of temperature

Temperature is one of the seven base SI (Le Système International d'Unités, Bureau International des Poids et Mesures (1991)) units, the others being the mole, kilogram, second, ampere, candela and metre. Many physical processes and properties are dependent on temperature and its measurement is crucial in industry and science with applications ranging from process control to the improvement of internal combustion engines.

The concept of temperature is familiar to us from our day-to-day experience of hot and cold objects. Indeed temperature can be defined qualitatively as a measure of hotness. Systems or objects can be ranked in a sequence according to their hotness and each system assigned a number, its temperature. Linked to the concept of hotness is heat transfer, the flow of thermal energy. It is a common experience that heat transfer will occur between a hot and a cold object. Temperature can be viewed accordingly as a potential, and temperature difference as the force that impels heat transfer from one object or system to another at a lower temperature.

The term 'system' is used to define a macroscopic entity, that is, one consisting of a statistically meaningful number of particles, that extends in space and time. An example of a system is the content of an internal combustion engine cylinder with the valves closed. Such a system can be described by specifying the composition of the substance, volume, pressure and temperature. A system is affected in two ways when its temperature rises. There is an increase in the disordered thermal motion of the constituents. The hotter a system is, the faster its particles move or vibrate. Similarly, the colder a system is, the slower the particles will move or vibrate, with a limit occurring when the particles can be considered to be in their most ordered state. As an example consider heating a solid whose atoms are initially vibrating in a lattice. As the temperature rises the atoms will vibrate more vigorously until a point is reached where the atoms can slide past one another and are not held in a fixed position and the substance is classed as a liquid. If more heating is provided raising the temperature further, then atoms will break away from each other breaking any bonds and become a gas. Further heating again will raise the temperature higher causing the molecules to increase their speed to a point where violent collisions between molecules ionizes them turning the gas into a plasma, containing ions and electrons. In addition to the disordered thermal motion of molecules, raising the temperature also excites higher energy states within the constituents of the system.

Although temperature as a concept is very familiar to us, its detailed definition has occupied the attention of many scientists for centuries. Much of our current understanding has come from the science of thermodynamics, the study of heat and work and the relevant physical properties. There are two approaches to thermodynamics: classical and statistical. Classical thermodynamics is predominantly concerned with the use of heating processes to do work, whilst statistical thermodynamics is concerned with linking quantum theory with the properties of matter in equilibrium. Either approach yields the same result for the definition of temperature. A summary of some of the definitions developed to describe temperature is provided in Table 1.1.

Quantitatively, temperature can be defined from the second law of thermodynamics as the rate of change of entropy with energy at constant volume, equation (1.1) (see, for example, Baierlein, 1999):

$$T = \frac{1}{(\partial S/\partial E)_{\mathrm{v}}} \tag{1.1}$$

where: T = absolute temperature (K)
S = entropy (J/K)
E = energy (J)
V = volume (m^3) or some other fixed external parameter.

Table 1.1 Some descriptions of temperature

Temperature is defined as the degree of hotness or coldness of a body.	M. Planck
The temperature of a system is a property that determines whether a system is in thermal equilibrium with other systems.	Zemansky and Dittman (1981)
Temperature is the parameter of state that is inversely proportional to the rate of change of the log of the number of accessible states as a function of energy for a system in thermal equilibrium.	Quinn (1990)

The definition given in equation (1.1) can appear abstract and for many applications the notion of temperature as a measure of hotness and temperature difference as a potential for the transfer of heat energy from one region to another is quite adequate. Nevertheless a quantitative definition of temperature is the basis of a substantial proportion of science, and it is a necessity for some temperature measurement applications, particularly those where temperatures are low or varying rapidly.

1.2 Temperature scales

In order to provide meaningful comparisons of temperature measurements made by different people it is useful to define a common scale. The definition of temperature scales is an arbitrary undertaking. One approach, referred to as the thermodynamic temperature scale, provides a linear scale that is valid for any substance and temperature range. The thermodynamic temperature scale is based on the ideal reversible Carnot engine cycle. The Carnot cycle consists of isothermal heat transfer at a high temperature, adiabatic expansion, isothermal heat transfer at a low temperature and adiabatic compression back to the high temperature. The Carnot engine efficiency is given by

$$\eta = 1 - \frac{T_2}{T_1} \tag{1.2}$$

where: η = efficiency,
T_1 = the high value of temperature at which isothermal heat transfer takes place in the cycle,
T_2 = the low value of temperature at which isothermal heat transfer takes place in the cycle.

Examination of equation (1.2) provides some insight into the concept of temperature and defines some bounds. Efficiency can never be greater than unity otherwise one would obtain more work out of a system than put in; a gross violation of the laws of physics. Efficiency equal to unity can only be achieved theoretically if T_2 is equal to zero or as T_1 approaches infinity. T_2 equal to zero therefore defines the lowest possible theoretical limit for temperature. As efficiency cannot be greater than unity, T_2 cannot normally be negative although negative absolute temperatures are possible and an example of this are temperatures experienced in a laser (see Purcell and Pound, 1951; Ramsey, 1962; Baierlein, 1999 for further insight into this subject).

The thermodynamic temperature scale provides a means of defining temperature in terms of equal increments of work outputs from ideal Carnot engines operating between two temperatures. In order to define a temperature scale all that is necessary is to decide the size of the increment. The two fixed temperatures used for the thermodynamic temperature scale are zero and the triple point of water. The triple point for a substance is the condition where solid, liquid and vapour phases co-exist simultaneously and this occurs at a unique pressure. The numerical value assigned to the triple point of water is 273.16. The SI unit of temperature is the kelvin, symbol K, and is defined as the fraction 1/273.16 of the temperature of the triple point of water.

The Celsius scale is also used to express temperature. The unit of Celsius temperature is the degree Celsius, symbol °C, and the magnitude of one degree Celsius is numerically equal to one kelvin. Temperature in degrees Celsius is related to that in kelvin by the equation

$$t = T - 273.15 \text{ (°C)} \tag{1.3}$$

where: t = temperature in degrees Celsius (°C),
T = temperature in kelvin (K).

Other scales in use include the Fahrenheit and Rankine scales with symbols °F and R respectively. The conversion relationships between these are given in equations (1.4) and (1.5):

$$T|_{°\mathrm{F}} = 1.8t + 32 \text{ (°F)} \tag{1.4}$$

where: t = temperature in degrees Celsius (°C),

$$T|_{\mathrm{R}} = T|_{°\mathrm{F}} + 459.67 \text{ (R)} \tag{1.5}$$

Whilst useful as an ultimate baseline, the thermodynamic temperature scale is not particularly practical. It is not actually possible to manufacture engines that operate on the Carnot cycle as minor inefficiencies in practical devices cause departures from the ideals demanded. Neither would it be desirable to have set up an elaborate configuration of thermodynamic cycles just to measure temperature. As a result, more practical methods have been proposed to define the temperature scale. The current internationally agreed scale is the International Temperature Scale of 1990 (ITS-90), which is described in Section 1.2.1.

1.2.1 The International Temperature Scale of 1990

The International Temperature Scale of 1990 (Preston-Thomas, 1990) is intended to be a practical internationally agreed best approximation to the thermodynamic temperature scale. It extends from 0.65 K up to the highest temperature practically measurable using the Planck radiation law (see Chapter 9, Section 9.2.1) and is believed to represent thermodynamic temperature within about ±2 mK from 1 to 273 K, ±3.5 mK (one standard deviation limits) at 730 K and ±7 mK at 900 K (Mangum and Furukawa, 1990). The ITS-90 is constructed using a number of overlapping temperature ranges. The ranges are defined between repeatable conditions using so-called fixed points such as the melting, freezing and triple points of a variety of materials. Fixed points are convenient as the conditions at which, say, the freezing of aluminium occurs can be set up in a highly reproducible fashion. The temperatures assigned to these are provided from the best estimates, using thermometers of an approved type, at the time of formulation of the ITS-90. Intermediate temperatures between the fixed points are determined by interpolation using specified equations. The five temperature ranges used in the ITS-90 are:

- 0.65 to 5 K defined in terms of the vapour pressures of helium 3 and helium 4
- 3 to 24.5561 K using a constant volume gas thermometer
- 13.8033 to 273.16 K using a platinum resistance thermometer
- 273.15 to 1234.93 K using a platinum resistance thermometer
- 1234.94 K and above using the Planck law of radiation.

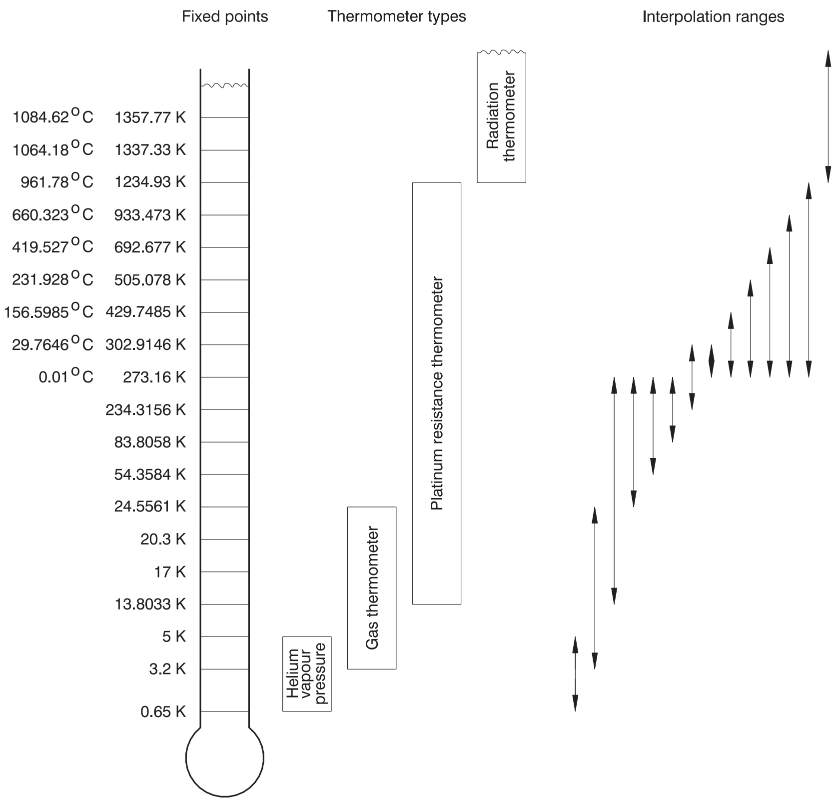

Figure 1.1 Simplified overview of fixed points and devices used for the ITS-90. (Data from Preston-Thomas, 1990.) Figure after Nicholas and White (1994)

Table 1.2 Defining points of the ITS-90 (Preston-Thomas, 1990)

Number	*Temperature (K)*	*Temperature (°C)*	*Substance*	*State*
1	3 to 5	−270.15 to −268.15	He	Vapour pressure
2	13.8033	−259.3467	H_2	Triple point
3	≈17	≈−256.15	H_2 or He	Vapour pressure
4	≈20.3	≈−252.85	H_2 or He	Vapour pressure
5	24.5561	−248.5939	Ne	Triple point
6	54.3584	−218.7916	O_2	Triple point
7	83.8058	−189.3442	Ar	Triple point
8	234.3156	−38.8344	Hg	Triple point
9	273.16	0.01	H_2O	Triple point
10	302.9146	29.7646	Ga	Melting point
11	429.7485	156.5985	In	Freezing point
12	505.078	231.928	Sn	Freezing point
13	692.677	419.527	Zn	Freezing point
14	933.473	660.323	Al	Freezing point
15	1234.93	961.78	Ag	Freezing point
16	1337.33	1064.18	Au	Freezing point
17	1357.77	1084.62	Cu	Freezing point

An overview of the fixed points, ranges and devices used in defining the ITS-90 is given in Figure 1.1. Table 1.2 provides details of the fixed points used and the temperatures assigned to these.

The significance of the ITS-90 is its value in providing a means of traceability between measurements taken in practical applications and a close approximation to thermodynamic temperature. This is illustrated schematically in Figure 1.2. In order for measurements to be traceable back to the ITS-90, sensors used for a given application should be calibrated against sensors that have a direct link to the ITS-90 (e.g. see UKAS, 2000). This can be achieved in a number of ways. A typical chain for an industrial measurement sensor might be calibration against another sensor that has itself been calibrated by a standards laboratory against a sensor that has been calibrated by a national standards laboratory. In this way the ITS-90 acts as a transfer standard of near thermodynamic temperatures to popular usage.

1.3 An overview of temperature measurement techniques

Temperature cannot be measured directly. Instead the effects on some other physical phenomena must be observed and related to temperature. There are many physical phenomena that are dependent on temperature such as

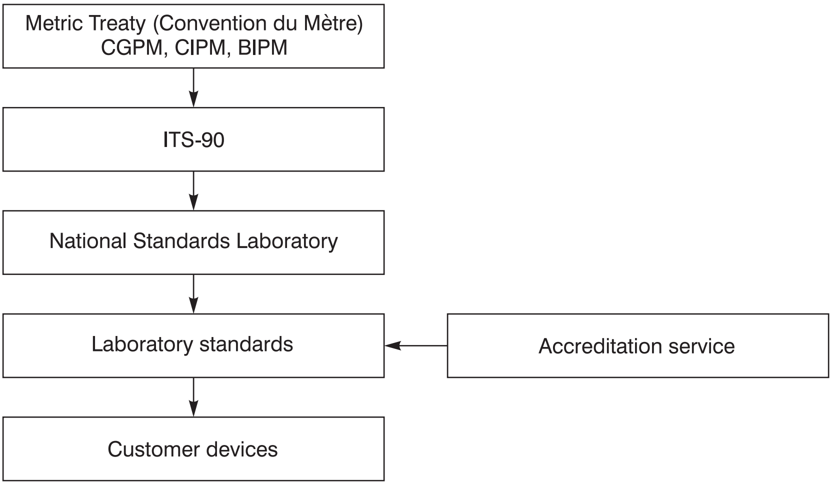

Figure 1.2 Recommended practice to ensure definition and traceability of temperature measurements. (CGPM = Conférence Générale des Poids et Mesures, CIPM = Comité International des Poids et Mesures, BIPM = Bureau International des Poids et Mesures)

resistance, volumetric expansion, vapour pressure and spectral characteristics. Many such phenomena have been exploited to produce devices to measure temperature. For convenience the various temperature measurement techniques can be classified according to the nature of contact between the medium of interest and the device. The categories used here are invasive, semi-invasive and non-invasive.

- Invasive techniques are those where the transducer is in direct contact with the medium of interest. An example is a liquid in glass thermometer immersed in a liquid.
- Semi-invasive techniques are those where the surface of interest is treated in some way to enable remote observation. An example is the use of thermochromic liquid crystals, which change colour with temperature. A surface can be sprayed with these and then observed remotely with, say, a CCD (charged coupled device) camera.
- Non-invasive techniques are those where the medium of interest is observed remotely. An example is the use of infrared thermometry where the sensor is located some distance away from the target material.

The terms ‘sensor’ and ‘transducer’ are commonly used in discussions on instrumentation. ‘Sensor’ is used here to describe the temperature-measuring device as a whole, while the term ‘transducer’ is used to define the part of the sensor that converts changes in temperature to a measurable quantity.