Appendix A: Overview of Thermometry

General thermometry and temperature scales

Thermodynamically speaking, temperature is the quantity in two systems which takes the same value in both systems when they are brought into thermal contact and allowed to come to thermal equilibrium. For example, if two different sized containers filled with different gasses at different pressures and temperatures are brought into thermal contact, after a period of time, the final volumes, pressures, entropies, enthalpies, and other thermodynamic properties of each gas can be different, but the temperature will be the same.

Thermodynamically, the ratio of temperature of two systems can always be determined. This allows a thermodynamic temperature scale to be developed, since there is an implied unique zero temperature. Additionally, it allows the freedom to assign a value to a unique state. Therefore, the size of a temperature unit is arbitrary.

The SI temperature scale is the Kelvin scale. It defines the triple point of water as the numerical value of 273.16, i.e., 273.16 K. The unit of temperature in this scale is the kelvin (K).

Another scale is the Rankine scale, where the triple point of water is defined as the value 491.688 °R (degrees Rankine). On the Rankine scale, temperature is 9/5 the Kelvin temperature.

The Kelvin and Rankine scales are both thermodynamic, however, other non-thermodynamic scales can be derived from them. The Celsius scale has units of °C (degrees Celsius) with the size of the unit equal to one Kelvin.

$$T(^{\circ}C) = T(K) - 273.15 \qquad \text{Eqn. 1}$$

While the Fahrenheit scale is defined as

$$T(^{\circ}F) = T(^{\circ}R) - 459.67 \qquad \text{Eqn. 2}$$

Additionally,

$$T(^{\circ}C) = [T(^{\circ}F) - 32]*(5/9) \qquad \text{Eqn. 3}$$

Both Celsius and Fahrenheit are non-thermodynamic temperature scales, i.e., the ratio of temperature is not related to thermodynamic properties (a 50 °F day is not two times “hotter” than a 25 °F day!) These scales are used for their pragmatic representation of the range of temperature that is experienced daily.

At the most basic level, a thermometer is a device with a measurable output that changes with temperature in a reproducible manner. If we can explicitly write an equation of state for a thermometer without introducing any unknown, temperature-dependent quantities, then we call that thermometer a **primary** thermometer. These include the gas thermometer, acoustic thermometer, noise thermometer, and total radiation thermometer. A **secondary** thermometer has an output that must be calibrated against defined fixed temperature points. For example, a platinum resistance temperature detector (RTD) is based on the change in resistance of a platinum wire with temperature.

Since primary thermometers are impractical (due to size, speed, and expense), secondary thermometers are used for most applications. The common practice is to use secondary thermometers and calibrate them to an internationally recognized temperature scale based on primary thermometers and fixed points. The most recent efforts in defining a temperature scale have resulted in the International Temperature Scale of 1990 (ITS-90) and the Provisional Low Temperature Scale of 2000 (PLTS-2000).

The ITS-90 is defined by 17 fixed points and 4 defining instruments. It spans a temperature range from 0.65 K to 10,000 K. For cryogenic purposes the three defining instruments are helium vapor pressure thermometry, gas thermometry, and platinum resistance thermometry.

For temperature below 1 K there is the Provisional Low Temperature Scale of 2000 (PLTS 2000). The PLTS-2000 is defined by a polynomial relating the melting pressure of He3 to temperature from the range 0.9 mK to 1 K. The pressure to temperature relationship is based on primary thermometers such as Johnson noise and nuclear orientation. Realization of the PLTS-2000 requires a helium-3 melting pressure thermometer (MPT). For the best realization of PLTS-2000, an MPT with an absolute pressure standard is used. This is a costly and time consuming method. Another method is to use the MPT as an interpolating instrument in conjunction with superconducting fixed points.

Few, if any, individuals or laboratories can afford the expense of maintaining the equipment necessary for achieving the ITS-90 and PLTS-2000. It is more customary to purchase thermometers calibrated by a standards laboratory. Even then, this thermometer is typically two or three times removed from primary thermometers.

Normally the temperature scale, once defined, is transferred from the primary thermometers to secondary thermometers maintained by government agencies, such as the National Institute of Standards and Technology (NIST), the National Physical Laboratory (NPL), or the Physikalisch-Technische Bundesanstalt (PBT). The most common of these secondary thermometers is the resistance thermometer, which is normally a high purity platinum or a high purity rhodium-iron alloy. Standards grade platinum resistance thermometers are referred to as standard platinum resistance thermometers (SPRT) while rhodium-iron resistance thermometers are referred to as RIRTs. Both materials are highly stable when wire-wound in a strain-free configuration. These standards grade resistance thermometers are maintained for calibrating customers' thermometers in a convenient manner. A standards laboratory would maintain a temperature scale on a set of resistance thermometers calibrated by that government agency. This is extremely expensive and time consuming. Thus, primary standards would not be used in day-to-day operation. Instead, the standards laboratory would calibrate a set of working standards for that purpose. These are the standards used to calibrate thermometers sold to customers. Each step in the calibration transfer process introduces a small additive error in the overall accuracy of the end calibration.

In addition to the sensor calibration process, there is also a class of sensors where the manufacturing process is highly reproducible. All of these sensors have a similar output to temperature response curve to within a specified tolerance. Industrial grade platinum thermometers and silicon diodes are examples of sensors that are interchangeable, i.e., their output as a function of temperature (R vs. T or V vs. T) is so uniform that any sensor can be interchanged with another—without calibration—and the temperature reading will still be accurate. The level of accuracy is specified by tolerance bands. With silicon diodes it is possible for a sensor to be interchangeable to within 0.25 K.

References:

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Fixed points

Repeatable temperature points are referred to as fixed points. These are simply points that occur reproducibly at the same temperature. There are numerous examples of fixed points. These include boiling points, freezing points, triple points, superconducting transition points, and superfluid transition points.

Figure 1 shows a typical pressure-temperature phase diagram. Matter can exist in three states: solid, liquid, and gas. The pressure-temperature diagram intuitively makes sense. If we heat matter to a high enough temperature, it becomes gaseous. If we subject matter to a high enough pressure, it becomes a solid. At combinations of pressure and temperature in between these limits, matter can exist as a liquid. The boundaries that separate these states of matter are called the melting (or freezing) curve, the vaporization (or condensation) curve and the sublimation curve. The intersection of all three curves is called the triple point. All three states of matter can coexist at that pressure and temperature. When we say the freezing point or boiling point of a substance is reproducible, it is implied that we are measuring that point at the same nominal pressure as in previous measurements. As is shown in the diagram, there is not a single freezing point or a single boiling point. There are an infinite number of freezing points and boiling points which form the boundaries between the solid and liquid states of matter. There is, however, a single triple point, which makes it inherently reproducible. There is only one combination of pressure and temperature for a substance that allows the triple point to be obtained.

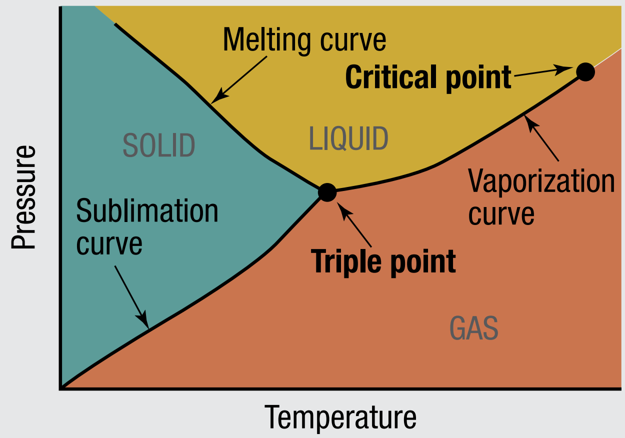

Figure 1 – generic pressure vs. temperature curve