

# Celsius or Kelvin: something to get steamed up about?

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The Celsius scale used to be a centigrade scale by definition. When the number of fixed points was reduced from two to one it became a centigrade scale by measurement. Now it is neither. What is going on?

The Celsius temperature scale was formerly called the centigrade scale since there were *by definition* a hundred degrees between the ice and the steam points of water, selected as the fixed points in this scale. The temperatures arbitrarily assigned to them were 0 and 100 degree Celsius, respectively. Now it is designated the Celsius scale after Anders Celsius (1701–1744), the Swedish astronomer who devised it in 1742.

In 1927, almost two hundred years later, the International Temperature Scale (ITS-27) was introduced, including the ice and the steam points as fixed points with the same temperatures assigned to them (Zemansky 1943). In 1948, the 9th General Conference of Weights and Measures attempted to secure international uniformity of nomenclature by abandoning the word 'centigrade' and its French equivalent 'centesimal' in favour of the name 'Celsius'. Thenceforth °C was regarded as the abbreviation of degree Celsius. At the 10th General Conference of Weights and Measures (1954), the Celsius scale was redefined in terms of a single fixed point (triple point of water) and the ideal-gas temperature scale. The value adopted for the triple point maintained the values 0 °C and 100 °C unchanged as far as the practical thermometry was concerned (Zemansky 1957). Thus, there was essential agreement between the old scale and the new Celsius scale, which continued being centigrade but now *by measurement*.

What is the present situation? This paper describes and analyses the origin and evolution of the Celsius scale in order to answer this question from a teaching viewpoint. The work ends with the conclusion that

now, in the absence of any other results which give further guidance, the Celsius scale no longer is centigrade *by definition* or *by measurement*.

## The old Celsius scale

The determination of empirical temperatures is based on the changes of physical properties of a selected reference system (thermometer) when it is put in thermal contact with some other systems. In order to make easier the process of determining temperatures, those systems with only one, easily measurable physical property,  $x$ , varying with temperature,  $t$ , are selected as thermometers. The choice of the function  $t = t(x)$  determines different temperature scales, the simplest corresponding to linear relations between  $t$  and  $x$ , such as  $t = ax$  as well as  $t = ax + b$ , where  $a$  and  $b$  are constants which can be obtained by measuring easily reproducible temperatures (fixed points) and assigning to them a particular value.

Until 1954, the common choice for the relation between  $t$  and  $x$  to define a temperature scale was based on  $t = ax + b$ , where the two constants could be obtained by specifying the temperature at two fixed points: the ice (i) and steam (s) points for water, which correspond, respectively, to the normal melting point and the normal boiling point of water, i.e. at 1 atm pressure. If we took the ice point as  $t_i = 0$  °C and the steam point as  $t_s = 100$  °C, we would construct a Celsius or centigrade scale of temperature (Zemansky 1943, Sears 1953). *By definition*, there were 100 Celsius degrees between the temperatures corresponding to the aforementioned fixed points, independently of the thermometric substance. Consequently, in the Celsius scale, the temperature could be expressed according to

$$t = 100 \frac{x - x_i}{x_s - x_i} \quad (1)$$

where  $x_i$  and  $x_s$  are the readings of the thermometer

at the fixed points, and  $x$  the reading at the temperature to be determined.

### The new Celsius scale

In 1854, Lord Kelvin suggested another temperature scale, based on only one fixed point. A hundred years later, the 10th General Conference on Weights and Measures agreed finally on adopting such a temperature scale, which could be defined by means of a constant-volume gas thermometer using the pressure of the gas as the thermometric parameter (ideal gas scale). We shall denote the temperature measured by means of an ideal gas according to this scale by  $\theta$ , its unit being the kelvin (K). The triple point of water (the temperature at which the three phases, solid, liquid and vapour, coexist at equilibrium, under the vapour pressure of 4.58 torr) was taken as the standard fixed point, and the temperature assigned to it was  $\theta_3 = 273.16$  K. If  $p$  and  $p_3$  are the gas pressures when the bulb of gas is immersed, respectively, in a system whose temperature is to be measured and in a system at temperature  $\theta_3$ , the gas scale temperature was determined from the expression

$$\theta = \theta_3 \lim_{p_3 \rightarrow 0} \frac{p}{p_3}. \quad (2)$$

The limit for low pressures is taken because the readings of two thermometers with different thermometric substances or with different amounts of the same gas will never coincide. This arbitrariness is removed if sufficiently rarefied (ideal) gases are used as the thermometric substances. In this case, all gas thermometers will give the same temperature irrespective of the gas used.

The temperature assigned to the fixed point might seem curious. Nevertheless, it was chosen to ensure that the sizes of the kelvin and Celsius degree were identical to the accuracy of available measurements. At this time, the experimentally determined temperatures of the ice and steam points in the ideal gas scale were

$$\theta_i = 273.157 \pm 0.030 \text{ K}$$

$$\theta_s = 373.157 \pm 0.030 \text{ K}$$

as calculated from Sears (1953).

Some other values obtained in the next decade gave

a slightly lower value for the steam point (Kestin 1966):

$$\theta_i = 273.1500 \pm 0.0002 \text{ K}$$

$$\theta_s = 373.1464 \pm 0.0036 \text{ K}.$$

From these latter values, it could be noted that the steam and the ice points differ by  $99.9964 \pm 0.0038$  K rather than the intended 100 K, which means that the sizes of the kelvin and Celsius degree would no longer be the same:

$$1^\circ\text{C} = 0.999964 \pm 0.000038 \text{ K}.$$

The discrepancy between the sizes of the degrees in the two scales is, obviously, a consequence of the accuracy of available measurements for  $\theta_i$  and  $\theta_s$ . For this reason, as more accurate techniques were developed, different sizes for the Celsius degrees could be found.

In order to overcome the dependence of the Celsius degree on the precision of experimental procedures, it could be redefined according to an ideal gas thermometer and imposing the condition that  $1^\circ\text{C} \equiv 1\text{K}$ , which leads to  $t_i - t_s = \theta_i - \theta_s$ . Adopting, *by definition*, the temperature of  $0^\circ\text{C}$  for the ice point, and taking into account that the relation between temperature and pressure is linear, we get

$$t = (\theta_s - \theta_i) \lim_{p_3 \rightarrow 0} \frac{p - p_i}{p_s - p_i} \quad (3)$$

for the temperature in the Celsius scale. The limit for low pressure has been taken again to make the gas closer to an ideal, avoiding thus the dependence of the temperature on the thermometric substance. Applying expression (2) to the ice and steam points, the Celsius scale temperature,  $t$ , is related to the ideal gas scale temperature,  $\theta$ , by

$$t = \theta - \theta_i \quad (4)$$

and then the ideal gas and the new Celsius scales are identical, apart from a shift of zero.

As can be observed, the range of this shift depends on the experimental determination of the ice point temperature,  $\theta_i$ . The main difficulty lies in setting up that point, i.e., ice and water coexisting in equilibrium with saturated air at a pressure of 1 atm, in a reproducible way (Zemansky 1957). The problem is that, as the ice melts, it tends to surround itself with

pure water, insulating it from the water saturated air. Hence, when the temperature of the ice point is measured with the gas thermometer, there can be variations in the measured value of  $p_i$ . Despite this fact, experimental determinations of the ice point by that time seemed to be, within the experimental uncertainties, rather stable and coincident. For this reason, the ice point was taken to be 0.01 K below the triple point of water in the aforementioned 10th General Conference on Weights and Measures, i.e.  $\theta_i = 273.15$  K, and

$$t(^{\circ}\text{C}) = \theta(\text{K}) - 273.15. \quad (5)$$

It would be noteworthy that the Celsius temperature unit is the degree Celsius ( $0^{\circ}\text{C}$ ), with the same size as the kelvin (K). As a result, a temperature interval can be expressed in either of the two scales. Moreover,  $\theta_i = 273.15$  K or  $t_i = 0^{\circ}\text{C}$  could be used for the ice point. More recent readings for the ice point still give a similar value (Kemp *et al* 1986).

The new Celsius scale is defined only for a gas thermometer according to expression (5) and has no meaning for other types of thermometer. Such thermometers may, however, read Celsius degree if they have been calibrated against an ideal gas thermometer giving Celsius degree (Finn 1993).

### State of the art

According to expression (5), the Celsius temperature for the boiling point of water will be

$$t_s(^{\circ}\text{C}) = \theta_s(\text{K}) - 273.15. \quad (6)$$

Although the determination of  $\theta_s$  by gas thermometry is also very sensitive to pressure changes (Zemansky 1957), the value  $\theta_s = 373.15$  K was included in the International Practical Temperature Scale of 1954 (IPTS-1954) when the new Celsius scale was adopted. As a consequence,  $t_s(^{\circ}\text{C}) = 100^{\circ}\text{C}$  and  $t_s - t_i = 100^{\circ}\text{C}$ , which means that the Celsius scale continued to be a centigrade scale, not by definition but *by measurement*. This situation remained stable for several years (Kestin 1966), and the IPTS-68 gave the same value (373.15 K) for the boiling point of water (Sears and Salinger 1976). Nevertheless, there was considerable activity in thermometry over the 20 years following the introduction of the IPTS-68, and the experimental determinations showed slightly

lower values for  $\theta_s$  (Quinn *et al* 1977, Martin *et al* 1988), which persuaded the members of Working Group 4 of the Consultative Committee for Thermometry to adopt another value for the boiling point (Rusby *et al* 1991):

$$\theta_s = 373.124 \pm 0.003 \text{ K}$$

and, from (6),

$$t_s = 99.974 \pm 0.003^{\circ}\text{C}$$

which leads to

$$t_s - t_i = 99.974 \pm 0.003^{\circ}\text{C}.$$

The boiling point proved to be so unreliable that the new International Temperature Scale of 1990 (ITS-90) did not include it as a fixed point (Preston-Thomas 1990), and it was no longer used as a secondary fixed point.

With these new readings for the boiling point, the Celsius scale has ceased to be centigrade not only *by definition* but also *by measurement*. What does this fact imply when teaching and researching on this subject? As far as teaching is concerned, this should seem surprising since the Celsius temperature scale has been taken to be a centigrade scale for more than two centuries. Nevertheless, among the textbooks on fundamentals of physics recently edited (after 1990), only one was found with updated information (Halliday *et al* 1993). Technical books and thermodynamics textbooks (Michalski *et al* 1991, Finn 1993, Anderson and Crear 1993, Van Wylen *et al* 1994) seem to provide further information in general. It is worthwhile to mention expressly the textbook by Zemansky and Dittman (1981), which incorporated the value 373.125 K for the boiling point of water, according to the information facilitated by Quinn *et al* (1977), updating the traditional value prevailing at that time corresponding to the IPTS-68 (373.15 K). Moreover, these authors seemed to suggest that the Celsius scale had ceased to be centigrade. According to the bibliography consulted concerning thermodynamics textbooks, and in the absence of any other sources which could give further guidance, this would be the first time in which a textbook contained such information. This fact clearly demonstrates the deep knowledge and intuition of these authors regarding thermometry related matters.

On the other hand, from a research viewpoint, although the deviation of  $t_s - t_i$  with respect to 100

K is only about 26 mK, this difference could be important for precision work and it could cause uncertainties at low temperatures (Finn 1993). Therefore, if the experimental value of the boiling point continues to decrease (about 26 mK during the last 27 years), a further recommendation from the General Committee on Weights and Measures would be welcome.

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