The Evolution of the Celsius and Kelvin Temperature Scales and the State of the Art

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The Celsius temperature scale was born centigrade *by definition* because there were a hundred degrees between the melting point of ice and the boiling point of water when these points were arbitrarily assigned temperatures of 0 and 100 °C, respectively. This scale is named in honor of Anders Celsius (1701–1744), a Swedish astronomer and physicist, who introduced it to the scientific community in a paper delivered to the Swedish Academy two years before his death (*1*). The Celsius scale is essentially empirical, because in this scale temperature depends on the thermometric property used.

The Kelvin scale was proposed in 1854 by the British physicist William Thomson (*2*) (afterwards Lord Kelvin) (1824–1907), on the basis of previous studies on thermal engines that describe a Carnot cycle. This scale is independent of the properties of the substance undergoing the cycle. As is well known (*3*), one of the ways of achieving the Kelvin or thermodynamic scale is by means of a gas thermometer and the ideal gas scale. In the old ideal gas scale, the two fixed points adopted were also the melting point of ice and the boiling point of water; although their corresponding temperatures were not assigned arbitrarily, their *difference* was taken as 100 K *by definition*.

In this work, the facts and circumstances that conditioned the evolution of the Celsius and the Kelvin temperature scales are described and interpreted. It is shown that in the temperature interval between the melting point of ice and the boiling point of water, both scales were born centigrade *by definition*; they were so as well *by experimental determination*, but they are not now centigrade *either* by definition or by experimental determination.

The Original Celsius and Kelvin Scales

The measurement of empirical temperatures is based on changes occurring in the physical properties of arbitrary reference systems (thermometers) when they are put in thermal contact with other systems. For the sake of simplicity, thermometers are chosen among systems where a particular convenient property *x* varies with temperature *t*. The arbitrariness of the function $t = \Omega(x)$ leads to the existence of different temperature scales (*4*) that correspond to simple mathematical functions containing a small number of constants. The values of the latter can be determined, as in any physical measurement, by selecting as many reference systems in easily reproducible states (fixed points) as there are constants in the function, and assigning an arbitrary temperature value to each of those states.

Until 1954 the function usually employed was linear, and the two fixed points were pure ice in equilibrium with air-saturated water at one standard atmosphere (the melting point of ice, or ice point) and pure water in equilibrium with its vapor at one standard atmosphere (the boiling point of water, or steam point). In the old Celsius scale, the tempera-

tures $t_i = 0$ °C and $t_s = 100$ °C had arbitrarily been assigned respectively to these fixed points (*5*). By definition, there existed 100 Celsius degrees difference between the fixed points, regardless of the thermometric property used. Therefore, temperature could be expressed in the form

$$t = 100 \frac{x - x_i}{x_s - x_i} \tag{1}$$

where x_i and x_s are the values taken by the thermometric property at the fixed points and x is its value at the temperature to be measured. It is important to stress that temperature thus defined depends on the choice of the thermometric property, except at the two fixed points. Even different varieties of the same kind of thermometer can lead to different results.

The discrepancies disappear in constant-volume gas thermometers, where gas pressure is the thermometric property. Although it is possible to define a Celsius temperature scale, these thermometers were actually used for temperature measurement in the so-called ideal gas scale. Since one way of achieving the thermodynamic temperature scale is by using a gas thermometer and the ideal gas scale (*3*), we may denote temperature by *T* on this scale, its unit being the kelvin (K). In the old ideal gas scale, the two fixed points selected were also the ice and the steam points, although their corresponding temperature values T_i and T_s were not arbitrarily assigned as in the Celsius scale. The *difference* $T_s - T_i$ was taken by definition equal to 100 K, and as a consequence the size of one Celsius degree is equivalent to the size of one kelvin, also by definition.

If p_i and p_s are the gas pressures when the thermometer is respectively at the ice point and at the steam point, the ratio of the temperatures T_i and T_s was defined (*6*) by means of the expression

$$\frac{T_s}{T_i} = \lim_{p_i \to 0} \frac{p_s}{p_i} \tag{2}$$

where the low pressure limit was taken so that the measurement of the temperature ratio was independent of the gas utilized. Any other temperature could then be determined by the expression

$$\frac{T}{T_i} = \lim_{p_i \to 0} \frac{p}{p_i} \tag{3}$$

where *p* is the gas pressure when the thermometer is in thermal contact with the system whose temperature is being measured. Since T_i had already been determined, the calculation of *T* was straightforward.

It is possible to express the Celsius scale in terms of the ideal gas scale, thus avoiding the dependence of the Celsius

temperature on the thermometric substance. If we use eq 1 for a gas thermometer with pressure as the thermometric property, we then have

$$t = 100 \lim_{p_i \to 0} \frac{p - p_i}{p_s - p_i} \qquad (4)$$

where the low-pressure limit has been taken for the reason mentioned above. By combining eqs 2–4 and imposing the condition that $T_s - T_i = 100$ K, one obtains

$$t = T - T_i \qquad (5)$$

In this way, the Celsius scale becomes identical to the ideal gas scale, except for the fact that its zero is shifted to the temperature T_i.

Determination of the exact value of T_i has been a major experimental problem to which many researchers have dedicated their attention for many years (7). Note that above room temperature, in converting Kelvin temperatures into Celsius ones or the other way round, small differences in the value of T_i used are immaterial; but at very low temperatures, this is not so (8). For example, assuming $t = -268.93$ °C and taking $T_i = 273.14$ K, one gets $T = 4.21$ K, whereas if $T_i = 273.17$ K, the result is $T = 4.24$ K, a discrepancy between the two values on the order of 1%. Evidently, at lower temperatures the percent error is larger. For practical purposes, it is sufficient now to mention that the best experimental value (until 1954) of the limit that appears in eq 2 was 1.3661 (9). This value leads to

$$T_i = 273.15 \text{ K}; \qquad T_s = 373.15 \text{ K} \qquad (6)$$

As a consequence of what had been established to then, in 1948 the IX General Conference on Weights and Measures adopted the following definition for the Celsius scale:

$$t(\text{°C}) = T(\text{K}) - 273.15 \qquad (7)$$

which obviously leads to the result $t_i = 0$ °C and $t_s = 100$ °C, meaning that in the interval between the ice and the steam points, the Celsius and the Kelvin scales continued being centigrade by definition. Similarly, the Celsius degree remained the same size as the kelvin, so that a temperature difference could then be expressed in either unit. Besides, the Celsius scale had been defined not only for a gas thermometer, but also for any other primary thermometer (that is, a thermometer that measures thermodynamic temperatures by using a physical law that includes thermodynamic temperature as a parameter), as well as for other secondary thermometers calibrated so that they measure thermodynamic temperatures.

The New Celsius and Kelvin Scales

In 1854, Lord Kelvin suggested the idea of defining a temperature scale with just a single fixed point (2). Giauque (10) in 1939 promoted the use of such a scale, which was finally accepted in 1954, the year of the X General Conference on Weights and Measures. The fixed point chosen was neither the ice point nor the steam point. The achievement of equilibrium between air-saturated water and pure ice is not at all easy to obtain in practice. When ice melts, it is surrounded by pure water, and this impedes the close contact between ice and air-saturated water. The boiling point of water is also

very sensitive to small pressure changes (3). Because of all this, the fixed point selected was the triple point of water (that is, the state where ice, liquid water, and water vapor coexist in thermodynamic equilibrium, at 4.58 torr), which is more easily reproducible than the ice point or the steam point. The temperature assigned to this fixed point on the new thermodynamic scale, and therefore on the ideal gas scale, was $T_3 = 273.16$ K.

As a consequence, if p and p_3 are the pressures exerted by the gas when the thermometer is in contact, respectively, with the system at temperature T, and with the ice–water–water vapor system, the temperature on the new ideal gas scale (9) is determined by the expression

$$\frac{T}{T_3} = \lim_{p_3 \to 0} \frac{p}{p_3} \qquad (8)$$

where, as usual, in the low-pressure limit the measurement of temperature is independent of the thermometric gas. Obviously, the ice and the steam points are now defined by

$$\frac{T_i}{T_3} = \lim_{p_3 \to 0} \frac{p_i}{p_3} \qquad (9)$$

$$\frac{T_s}{T_3} = \lim_{p_3 \to 0} \frac{p_s}{p_3} \qquad (10)$$

Therefore, one of the consequences of accepting the definition given in eq 8 is to make the temperature interval between the ice and the steam points an experimentally determined quantity, subject to future modification, depending on more accurate determinations of T_i and T_s (11).

It may seem striking that the value chosen for the temperature of the triple point of water was not rounded off or replaced by a simpler one. The reason was, paradoxically, of a practical nature. The value assigned to the triple point of water resulted from experimental measurements obtained using gas thermometers calibrated at the ice and steam points. Therefore, the temperatures of those points on the new ideal gas scale had to be kept unchanged. In this way, the definition given by eq 7 was still valid and, in consequence, the Celsius scale zero was 0.01 K below the triple point of water. Equation 7 itself allows us to affirm that in the temperature interval between the ice and the steam points, the Celsius scale and the Kelvin scale continued being centigrade, not by definition now but *by experimental determination*.

The Present Celsius and Kelvin Scales

The situation described above slightly changed in the following years. Thus, as an example, the following values (12) are representative of the decade of the 1960s:

$$T_i = (273.1500 \pm 0.0002) \text{ K}; \quad T_s = (373.1464 \pm 0.0036) \text{ K} \quad (11)$$

and, according to eq 7, they lead to

$$t_s - t_i = (99.9964 \pm 0.0038) \text{ °C} \qquad (12)$$

As a consequence, of the fixed points that define the International Practical Temperature Scale of 1988 (IPTS-68), the steam point still has the value 373.15 K. The ice point appears as a secondary reference point, also with its same value,

273.15 K (*13*). New experimental determinations of the steam point, together with previous unpublished measurements, show that in the decade of the 1970s (*14*), the difference between the value of $T_s - T_i$ and 100 K could be as large as 35 mK. However, in the IPTS-68 (amended 1975 edition) (*15*), the values assigned to the ice and steam points are again the traditional ones. In 1977, the members of Working Group 3 of the Consultative Committee for Thermometry (CCT) published the official best estimate for the steam point temperature (*16*):

$$T_s = (373.125 \pm 0.003) \text{ K} \tag{13}$$

Thus, again according to eq 7,

$$t_s = (99.975 \pm 0.003) \text{ °C} \tag{14}$$

and

$$t_s - t_i = (99.975 \pm 0.003) \text{ °C} \tag{15}$$

Thus, the Celsius and the Kelvin scales ceased being centigrade *by experimental determination* in the temperature interval between the ice and steam points. These results were confirmed in following years (*17, 18*), leading to the highly significant fact that, *for the very first time, the steam point of water was not included*, even as a secondary fixed point, in the International Temperature Scale of 1990 (ITS-90) (*19*). This point has been replaced by the melting point of gallium (29.7646 °C) and the melting point of indium (156.5985 °C), the former providing a very convenient, highly reproducible, and stable (0.2 mK) room temperature reference temperature for many applications (*20*). In 1991, the members of the CCT Working Group 4 published the thermodynamic basis of the ITS-90 (*21*), giving for T_s the value

$$T_s = (373.124 \pm 0.003) \text{ K} \tag{16}$$

which is the one currently accepted. This value coincided with that obtained in 1976 by Guildner and Edsinger (*22*) by means of gas thermometry. At its 18th Meeting in 1993, a list of the temperatures associated with a number of secondary reference points was presented by Working Group 2 of the CCT. The committee recommended that this list be revised in accordance with the suggestions of various members and published. Finally, the recommended values of temperature on the ITS-90 for a selected set of secondary reference points (*23*) include for T_s the value

$$T_s = (373.124 \pm 0.001) \text{ K} \tag{17}$$

Evidently,

$$t_s = (99.974 \pm 0.001) \text{ °C} \tag{18}$$

and so

$$t_s - t_i = (99.974 \pm 0.001) \text{ °C} \tag{19}$$

We have now shown that in the temperature interval between the ice and steam points the Celsius and the Kelvin scales, born centigrade *by definition*, actually became so afterwards *by experimental determination*, but are not so any more, *either* by definition or by experimental determination.

Acknowledgment

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