Heat Transfer 1986

Proceedings of
The Eighth International
Heat Transfer Conference
San Francisco, CA U.S.A.

IHTC
1986

Volume
1
Plenary and Keynote Papers

Edited by C. L. Tien, V. P. Carey, and J. K. Ferrell

in cooperation with the members of
The International Scientific Committee
and The U.S. Scientific Committee

FAHRENHEIT A PIONEER OF EXACT THERMOMETRY

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Abstract

1986 is the 300th anniversary of Fahrenheit's birth, reason enough to reflect upon the life and work of this man, whose temperature-scale - despite metrification - is still in use today in the English-speaking world.

There are two issues, in particular, which we might consider: On what basis did Fahrenheit's scale achieve such a widespread distribution? From where did he derive the striking temperature-values for his scale (32 for the ice-point and 212 for the steam-point), which belong neither to a metrical nor to a foot-pound-second-system?

Before dealing with his thermometers we need to consider the background of Fahrenheit's life.

1. FAHRENHEIT'S LIFE

1.1. Origins and Youth

Daniel Gabriel Fahrenheit was born on May 24th, 1686 in Danzig, the eldest son of the merchant Daniel Fahrenheit and his wife Concordia, née Schumann. Daniel Fahrenheit had been made a freeman of the town in 1684, and together with his partner Ulrich Isenhut, ran a successful trading business, which also maintained a branch in Amsterdam. Fahrenheit's parents owned several properties in the centre of Danzig, including Daniel Gabriel's birthplace at Hundegasse 94, as well as a country house near Danzig [1].

Fahrenheit's grandfather, Reinhold, had arrived in Danzig in 1650 from Königsberg. As recent investigations [2] have shown, the family had earlier come from Hildesheim. An ancestor of our Daniel Gabriel, Hans Fahrenheit, had moved from Hildesheim via Rostock to Königsberg, where he was made a freeman in 1512.

Daniel Gabriel was the eldest of five children - he had two brothers and two sisters. He received private tuition until he was twelve, when he started to attend the Marienschule in Danzig (1698). He was due to transfer to the local gymnasium in 1701 "since his particular eagerness to learn had been noticed" [3]. This plan was not to be realised, however, since on August 14th, 1701 both parents died at the country house. The cause of their deaths has been attributed by some to mushroom poisoning [4], whilst others suggest that poison was accidentally mistaken for medicine [1].

Since the five children were still minors, the city council nominated three Danzig citizens as guardians: they decided that Daniel Gabriel, as the eldest, should start a merchant apprenticeship in order to succeed his father in the family business. In 1702, after receiving an in-house training in bookkeeping, he was sent as a sixteen-year-old apprentice to the merchant Herman von Beuningen in Amsterdam. He managed to see through the four years of his apprenticeship (1702-1706), although his conduct was not always to the satisfaction of his guardians and patrons. It seems likely that Fahrenheit started his scientific studies quite early, to the detriment of his mercantile education. During these years in Amsterdam he must have come to the decision that he would rather manufacture physical and meteorological instruments - and, in particular, thermometers and barometers, for which there was a great need at that time - than continue as a merchant. He was already engaging in this new occupation during at least the later years of his apprenticeship, and when this was completed, he absorbed himself totally in his experiments. After he had borrowed money to further his experiments, it was eventually necessary for his guardians to pay his debts from his inheritance [5]. Subsequently, on January 21st, 1707, they succeeded in obtaining an authorization from the city council of Danzig [6] for an Amsterdam merchant to have Fahrenheit detained by the police and then deported by the East India Company to the Dutch East Indies. Fortunately for thermometry, Daniel Gabriel could be neither detained nor deported, since he was not to be found: he was travelling.

1.2. Years of Wandering

In the decade between 1707 and 1717 Fahrenheit was almost continually on the move. The unknown biographer wrote of this in 1740 [3]:

> "To this end he made many arduous journeys by land and sea, conferred with the most famous mathematicians in Denmark and Sweden and dispatched his instruments to Iceland, Lapland and other places from where interested correspondents reported observations to Amsterdam, so that in this extremely cold year (1740), a number of articles have made reference to the remarkable observations made by Fahrenheit's weather-glasses during the hard winter of 1709."

The first of these journeys, which led him through Germany, Sweden and Denmark, brought him in 1708 to Copenhagen, where he met the Danish astronomer Olav Roemer [7], who was also involved with thermometry. The meeting with Roemer was described in detail by Fahrenheit [8] and we will comment upon this in the second half of this paper. Here we need only to notice that by 1708 Fahrenheit was already in possession of his own thermometers, since, according to his account, the discussion with Roemer inspired him to improve on his instruments.

With the completion of his 24th year on May 24th, 1710, he reached his legal adulthood, so that the basis of the earlier court-order disappeared. Since no document declaring his majority exists, he cannot have been in Danzig at this time, although later that year, after the end of the great plague, he visited his brothers and sisters in Danzig and remained there until the following year. On January 20th, 1711, his younger brother Ephraim was (prematurely) declared adult. Both brothers declared before the court that they had each received their rightful inheritance from their guardians [1]. After this, Fahrenheit recommenced his travels with journeys to Kurland and Livland, as we know from letters of authority which were made out in Königsberg and Mitau [1]. In the years 1712/13 he was once more in Danzig, where he worked with a friend, the gymnasial Professor, Paul Pater. In 1713/14 he was in Berlin where he delivered one long and four short thermometers to the Academy of Science [9], before continuing his journey to Dresden, Halle and Leipzig. On the way he visited local glass-blowers to learn about the manufacture of capillaries for his thermometers and to perfect his glass-blowing technique.

On this journey he met Christian Wolff [10] in Halle (1714), where the latter was Professor in mathematics. Fahrenheit gave him two wine-spirit thermometers, which, despite differing capacities, gave practically identical readings over their whole range. Wolff recognized immediately the fundamental significance of this development and described in detail his evaluation in the "Acta Eruditorum" [11]. Although Fahrenheit was clearly certain of his achievement, this independent confirmation provided a valuable recommendation.

Despite his intensive travels, Fahrenheit did not limit his creativity solely to thermometers and barometers: on March 5th, 1715 he wrote from Leipzig [8] to Leibniz [12], asking him for his comments on a quicksilver clock, which he had designed in connection with a competition set up by a British parliamentary commission. In his reply, Leibniz suggested that more details would be required to satisfy the requirements of the commission. Previously, Leibniz had asked Wolff's opinion of Fahrenheit, and in his answer Wolff mentioned a perpetuum mobile [13], upon which Fahrenheit had asked him to comment. Wolff further observed: "He deserves recognition for his efforts in the construction of thermometers and barometers; he is, however, too little experienced in the science of mathematics and in his inventions chance plays a bigger role than thought." [6]. However, this judgement was not in respect of Fahrenheit's corresponding thermometers which Wolff had strongly praised in 1714. In a further letter from Fahrenheit to Leibniz (dated June 1st, 1716 in Dresden [8]) he writes of a mirror-telescope, the construction of which is delayed by a lack of money, and he requests references to help him secure regular employment - a sign that his financial situation was none too rosy. Leibniz' death in 1716 prevented a response and possible help.

In 1717, at the age of nearly 31, Fahrenheit arrived in Amsterdam and finally settled down: the years of wandering had come to an end.

1.3. Fahrenheit in Amsterdam

In Amsterdam, Fahrenheit set up his home and workshop in the house of the coppersmith Roemer at the corner of Leidsche Straat and Keizersgracht. It was here that he began to construct quicksilver thermometers, for which he had already made preliminary experiments in Berlin during the early part of 1713. Of special significance during this time in Amsterdam was his relationship to the influential Dutch scientists of the day, and his scientific lectures. His connection to the Professor of medicine and chemistry, Herman Boerhave [14], has provided us with 15 letters [8] from Fahrenheit, which reveal to us details of his life, his technique for manufacturing thermometers and the results of his scientific experiments using these accurate thermometers. He also met and corresponded with s'Gravesande [15] and van Musschenbroek [16], who, like Boerhave, were using Fahrenheit's thermometers and praised his skill in their production. From 1718 onwards Fahrenheit gave lectures on scientific topics and the announcements and transcriptions of these have survived to the present day. The themes were optics, hydrostatics and chemistry. In addition, he was making experiments which were only partially concerned with the fabrication of thermometers and barometers: for instance, on the boiling-points of liquids, the expansion of quicksilver in tubes made from glass of various provenance (Potsdam, Bohemia, Thüringen, England, Amersfoort and Amsterdam), the subcooling of water, the density of liquids and the development of an araeometer, the dependence of the boiling-point of water on barometric reading and the production of cold by salt-mixtures. During 1724 he travelled to London in response to an invitation to become a member of the Royal Society, and whilst there, he gave a lecture on the density of a metal - often found in association with gold - which was then known as lead-gold and which is probably platinum [17]. In addition, during the same year, five essays were published in "Philosophical Transactions" [18], and these, together with the letters to Boerhave, are the richest source of information on his activities [19].

The closeness of his contact with Boerhave is revealed by Fahrenheit informing him of his marriage plans. On March 20th, 1729 he writes:

> "......that, since I am tired of staying temporarily with different people, I am now busying myself with finding a loyal woman."

But by April 17th that year he reports:

> "I had often been entertained by this lady (who already possesses a pretty penny), but her friends, who expect to inherit from her, fearing the loss of this beneficence have ensured that my hopes came to grief" [6].

There is no mention of further similar efforts, and he remained a bachelor.

Fahrenheit's last project was a machine for lifting water, which was intended for use in draining flooded areas. He had completed a model of this and applied for a patent from the "Staten van Holland en West-Friesland", and this was in fact granted. In order to deal with this matter, he travelled in September 1736 to The Hague, where he was suddenly taken ill. On September 7th he summoned a notary to the "Frisleven Inn", where he dictated his will. In this he left the water machine and half of any future income from the patent to s'Gravesande [4,6].

Fahrenheit died on September 16th, 1736 in The Hague at the age of fifty and was buried four days later in the monastery-church. It was a fourth grade burial - a pauper's burial. As a result of rebuilding and reorganisation, his resting place cannot now be located. His belongings were auctioned on December 5th, 1736 in his last dwelling place-Prinsengracht near the Nieuwe Spiegelstraat- and so were scattered to the winds. There is no record of a portrait of Fahrenheit and none has ever been found.

2. FAHRENHEIT'S WORK

2.1. The beginnings of thermometry

The influence of heat on the volume of physical bodies is particulary striking in the case of gases. It is therefore not surprising that the oldest instruments for the measurement of temperature used a gas - air - as their medium. Some people ascribe the earliest invention of these to Galilei [20], others to the Dutchman Cornelius Drebbel [21], but for both approximately the same date is quoted (around 1592) [22]. Figure 1 shows a Drebbel gas thermometer (there fig. 10) with a hanging liquid column and an Amontons thermometer (there fig. 12), with a standing liquid column. The readings in both cases were dependent on atmospheric pressure. Sanctorius (1561-1636), professor of medicine and anatomy in Padua, used an air thermometer for the measurement of fever, and its application is shown in figure 2. The normal body temperature was indicated by a mark on the capillary.

Then, as today, the gas thermometer did not enjoy widespread success - as the result of its complicated method of use – and it was replaced by the liquid thermometer. This could be used in any situation and its readings were not dependent on atmospheric pressure; it could also be easily produced in smaller sizes. The development of the liquid thermometer owed much to a group of Italian scientists, who came together in Florence in the middle of the 17th century .

2.2. Accademia del Cimento

After Galilei's death in 1642, a group of his students joined together in Florence, and continued scientific experiments in the spirit of their master. Since the Grand Duke of Tuscany, Ferdinand II (1610 – 1670), was also an admirer of Galilei and a friend of the natural sciences, he made his own rooms available for the meetings of this group of scientists, so that at the Florentine court a form of private academy developed. From this evolved the "Accademia del Cimento", which was formally founded in 1657 by the Grand Duke [23]. The patron was his younger brother, Leopoldo de' Medici (1617 – 1675). The Academy existed for only ten years, but during this extremely fruitful period, instruments were developed which long outlived their inventors. A full account of its activities has been preserved in the Proceedings, which were published by the Secretary of the Academy in 1667, the year of its dissolution [24]. Many of the instruments used and developed by the Accademia del Cimento are today to be found in the "Museo di Storia della Scienza" in Florence [25].

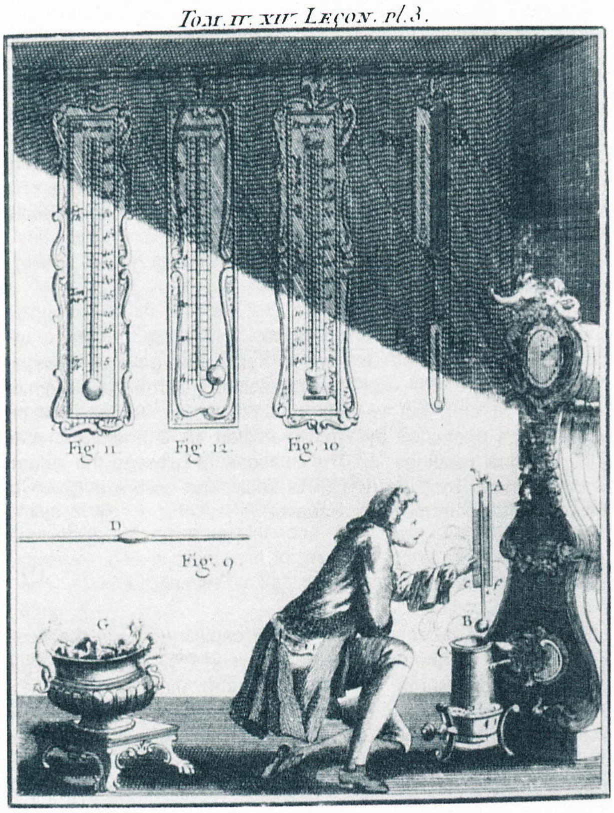

Fig.1: Thermometry about 1750
Fig. 10 air – thermometer according to Drebbel.
Fig. 12 air – thermometer according to Amontons
Fig. 11 Florentine thermometer using wine – spirit, top right travelling thermometer, below the calibration of the steam – point and ice – point. Nollet: Leçons de Physique Expérimentale. Paris 1764

Among these instruments are examples of the "Florentine thermometer", one of the oldest liquid thermometers in the world, which was in widespread use under this name until at least the end of the 18th century [1]. It is a wine – spirit – in – glass thermometer, and consists of a globe reservoir melted onto a capillary, which is sealed at the upper end (fig.3, I to III). The scale – points are drops of black enamel melted onto the capillary. Every 10th drop is white and every 100th drop red [23]. The Academy used thermometers with scale – lengths of 50, 100 and 300 to 400 degrees.

For calibration, two extreme points were taken: the coldest winter temperature in Florence (which probably lies a little below the ice – point) and the hottest summer temperature. However, these temperatures lie at different scale points for each thermometer type. As a result of the use of these unreliable fixed points, satisfying correspondence within a series of thermometers could be achieved only through the skill of the glass – blower. The spiral thermometer in fig.3,IV, deserves special mention, since although it gilds the lily somewhat, it does indicate the extreme skill of the Florentine glass – blowers; the spiral is about 10 cm high and the lower reservoir has a diameter of 6.8 cm.

The use of the Florentine thermometer quickly spread. This is true not only for those instruments which came directly from the Academy, but even more so for those which, following the dissolution of the Academy, were produced by other instrument – makers outside Florence (but predominantly Italian) and often distributed via travelling salesmen. As a result of these developments the Florentine thermometer suffered a number of changes. Lambert comments [22b]:

> "These people diverted greatly from the thoroughness practiced by the Florentine Academy in the production of their thermometers. And consequently complaints arose everywhere that the thermometers had no comprehensible scale and that they were by no means corresponding. It

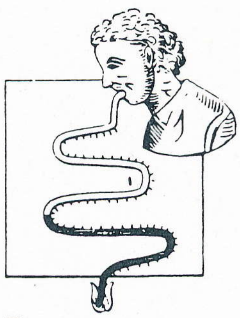

Fig. 2

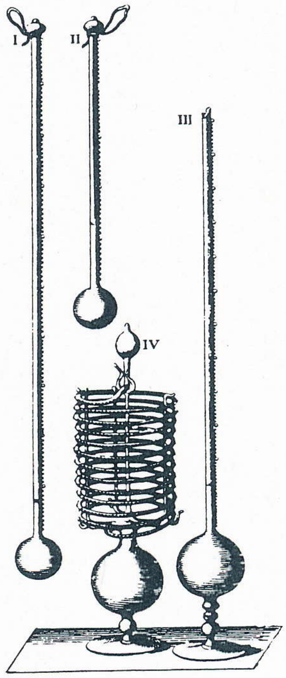

Fig. 3

Fig.2: Fever measurement with an air – thermometer according to Sanctorius [29e].

Fig.3: Florentine thermometer: I 100 degrees, II 50 degrees, III 300 – 400 degrees, IV spiral thermometer.

went so far that the thermometer itself was blamed and attempts were made to show that changes in the readings between adjacent thermometers were neither equal nor even proportional."

Such complaints concerning the lack of correspondence were widespread by the end of the 17th century and the beginning of the 18th century and could be exemplified by further quotations. Later thermometer-makers lacked the experience of the Florentines in balancing the reservoir size, the diameter of the capillary (the calibre) and the liquid-volume. It may also be, as Lambert suggests, that the capillary-diameter was not constant – that is, there was a calibre-error – so that the readings could no longer be proportional.

A further change from the Florentine thermometer concerned the scale. The thermometers of the Academia del Cimento had enamel drops melted onto the capillary as scale-points – as described above – but without further labelling or numbering. This is true for all examples which can still be seen today in Florence [25].

However, later models, although called "Florentine thermometers" had their capillaries firmly attached to a board, on which was inscribed a scale with numbers and labelling (compare fig.1, fig.11). At that time it was thought that warmth and cold are two opposing natural forces which are in balance at the zero-point (that is "temperate"). This temperature can be experienced in deep, closed cellars where "one feels neither warm nor cold", that is for us about 12°C to 13°C. As Momber [1] reports, up until the middle of the 19th century a Florentine scale was understood to be based on such a middle temperature and to measure between 90 and 100 degrees in each direction.

In addition to this scale, numerous others have been developed in the course of time each with different "fixed points" and numeric values. In the table published by Lambert [22b] in 1779, nineteen temperature scales are listed. Only few of these fulfil the strict conditions of scientific thermometry. Most were fluid thermometers with the temperature being considered proportional to the volume [26].

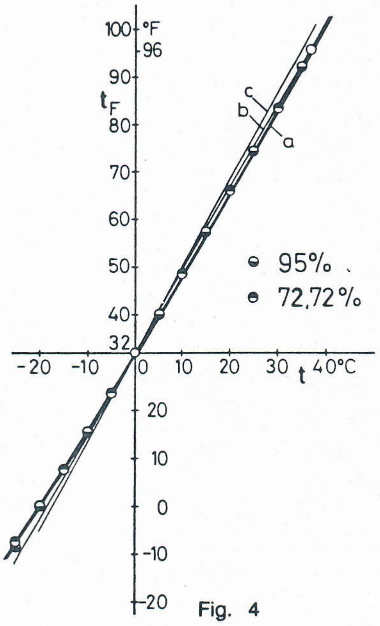

Fig. 4

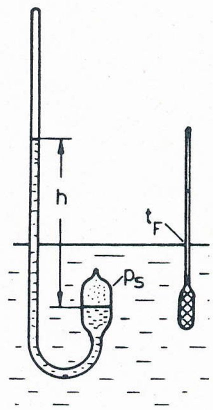

Fig. 5

Fig.4: Scales of corresponding thermometers (Halle 1714) for wine-spirit of 95% and 75.72% as a function of the Celsius temperature.

Fig.5: Apparatus for the measurement of the steam pressure of water, 1723. The glass tube on the left is 130 cm long. Not to scale. h: height of the quicksilver column, p_s: saturation pressure of water, t_F: Fahrenheit temperature.

In his search for a "natural" measure of temperature Amontons [27] (1663–1705), using an air thermometer with quicksilver as barrier-liquid, discovered that the pressure of the enclosed air is always increased by the same proportion (about a third) of the initial pressure when the thermometer reservoir is transferred from cold water into boiling water. This holds true for all initial pressures and volumes. Since the air pressure can be used as a measure of temperature (always taking into account atmospheric pressure) it is possible to construct a natural temperature-scale for which the zero-point is equivalent to zero pressure. Amontons suggested that such an air thermometer should be used for the calibration of fluid thermometers in order to avoid the limitation of the existing conventional scales. These proposals, although taken up by Lambert [22b], achieved no acceptance. The full significance of these proposals was only recognized in 1948 when the 9th General Conference of Weights and Measures used it for the definition of a thermodynamic temperature-scale.

The situation as Fahrenheit found it was this: Florentine thermometers were in widespread use, although their quality had deteriorated since the time of the Accademia del Cimento, and complaints about the lack of correspondence were common. In addition, there were numerous thermometer-types with local distribution, but it is doubtful if any of these fulfilled the conditions of correct temperature measurement. Proposals for further development – as, for example, made by Newton or Amontons – attracted little or no attention. The interest in temperature measurement was, however, great: the Academies of London, Paris and Berlin, as well as individuals in Florence, Danzig, Kiel, Copenhagen and elsewhere were making continuous observations of air-pressure and temperature. For an instrument-maker who was more able than his competitors, the prospects were good.

2.3. Fahrenheit's First Thermometers

The corresponding thermometers of Halle. The two corresponding thermometers which Fahrenheit gave to Christian Wolff in Halle in 1714 had identical scales (with an approximate length of 16 cm), but vessels with differing volumes. For the whole range examined by Wolff (between 10°C and 30°C) they gave identical readings [11]. The relationship between the volume of thermometer medium, length of scale and calibre is given by the elementary thermometer equation:

$$\frac{V_t}{V_0} - 1 = \frac{q\, L_t}{V_0} \qquad (1)$$

where q is the cross-section of the capillary , L_t is the scale length for the temperature interval between 0°C and t, and V_0 is the combined volume of the vessel and that section of the capillary below the zero-mark. In this it is assumed that the expansion of the glass compared to that of the wine-spirit can be neglected and that no further corrections – for calibre-irregularities, exposed thread etc. – are necessary. The reference temperature is 0°C, as is conventional but not essential. Since the scale length L_t in both of Fahrenheit's instruments was the same, but the vessel volumes (that is basically V_0) differed, Fahrenheit had to choose capillaries so that the proportion q/V_0 remained constant if he used alcohol of the same concentration in both thermometers. However, by using two different concentrations of alcohol – that is, changing the left side of equation (1) – he had an alternative method for adjustment.

In order to investigate this, the Fahrenheit temperature can be plotted against the Celsius temperature, with 32°F set equal to the zero-point of the Celsius scale (0°C), and 96°F set equal to 37°C. This is shown in fig.4. In this case the zero-point of the Fahrenheit scale is equivalent to −20°C, since the two scales do not have a linear relationship. The deviation from linearity (the thin line in fig.4) is not very great, about 0.5 K at around 20°C and 1.5 K at −20°C. From this presentation one can accept that Fahrenheit did indeed use the eutectic temperature of the ice-sodiumchloride system as the zero-point for his scale of 1714, as he asserts in his own description [18b]. The relationship between Fahrenheit and Celsius temperatures for two differing concentrations of wine-spirit – namely 95% and 72,72% – found in our own experiments is shown in fig.4. It may be seen that, within the limits of graphical representation, the calculated points lie on the same curve.

From all this we may observe:

1. Fahrenheit's particular "trick" in the production of his two corresponding thermometers of 1714 was that he used well-defined fixed points, although he only described this in his second publication of 1724 [18b].

2. We think that it is very probable that Fahrenheit wanted the eutectic temperature of the NaCl-ice-system (−21,2°C) as the temperature of his zero-point and that he achieved it to an uncertainty of about ± 1 K.

3. Since the length of the scale was fixed, the correspondence of the thermometers could be achieved by the adjustment of calibre and liquid volume, as equation (1) shows.

4. A further adjustment was possible through the use of differing concentrations of wine-spirit, which – as shown in fig.4 – did not alter the correspondence of the two thermometers. This also indicates that the concentration of wine-spirit (within certain limits) has no effect in thermometry.

5. Christian Wolff thought the two corresponding thermometers to be such a great development that he devoted a two page article to them in the "Acta Eruditorum". According to Lambert [22b] the thermometers displayed "to Wolff's astonishment, extraordinary correspondence" – ("Wolff didn't realize the artifice, since he looked for it in the salts").

6. The fabrication of two corresponding thermometers with a fixed scale – which enabled prior printing – opened up the possibility of mass production. On these, the thermometer reservoir has a cylindrical form – and no longer a spherical one –, as suggested by Fahrenheit to minimize the response time.

Fahrenheit and Roemer. Prior to giving his two thermometers to Christian Wolff in 1714, Fahrenheit had already met Olav Roemer in Copenhagen in 1708. Roemer was about to calibrate his self-manufactured wine-spirit thermometers which he needed for a series of meteorological measurements, using a technique that Fahrenheit described and may be summarized as follows:

The thermometers were placed alternately in ice and warm water and the heights of the liquid column were marked. The interval between these points was halved and subtracted from the lower reading to give the zero-point. The ice-point had been given the value 7.5° so that the warm-water-point had the value 22.5°.

This peculiar gradation finds its explanation in Roemer's proposals in his "Adversaria" [7]. In this a scale of 60° is proposed, in which the highest temperature is that of the steam-point. These 60° are divided into 8 parts – each of 7.5° – so that the ice-point is at 7.5°, allowing 7.5° to the zero-point for frost measurements. It is not established whether Roemer used the full length of this scale, an issue also mentioned by Dorsey [28]. Roemer does not describe the difficulties of trying to measure the steam-point [29] with a wine-spirit thermometer. Assuming Roemer's scale to be linear, his zero-point is equivalent to −14.3°C and the temperature of warm water to 28.6°C.

When Fahrenheit describes the improvement of his thermometer, he seems to refer to his utilization of only the principle of Roemer's scale with its minimum- rather than middle-based scale, but in which he substitutes the factor 8 for the inconvenient factor 7.5 and subdivides each degree into four . This is the source of the value 32 (= 4 x 8) for Fahrenheit's ice-point which has remained until today. According to Fahrenheit himself it is based on pure chance.

Fahrenheit's oldest scale. These considerations lead directly to the question of how the scales of Fahrenheit's first thermometers from the years 1706 or 1707 might have looked. His biographers generally agree (particularly van Swinden [22a] and Lambert [22b], but also Burckhardt [22c] and Momber [1]) that it was a scale of the Florentine type (see section 2.2) but for which he was already using the fixed points of his second scale (...."whilst keeping the degrees of the original in the process of these changes") [22b].

If we accept this viewpoint – and there appears to be no counterargument – we come to some remarkable conclusions concerning Fahrenheit's person and work:

1. Fahrenheit had already established the fundamental principle of his work – that thermometer scales should only be defined by reproducible fixed points – extremely early at the age of twenty or twenty-one.
2. As a result of this principle, the Florentine-type scale which he used – but which by then had hardly anything in common with the original thermometers of the Florentine Academy – was put on a firm basis.
3. When he visited Roemer in Copenhagen, Fahrenheit already had an established concept. However, he learned that the zero-point of a scale does not necessarily have to be a fixed point. This understanding he probably applied later to the scales of his quicksilver (mercury) thermometers (see section 2.4).
4. Fahrenheit must have set up a workshop in Amsterdam, since the scaling of the three fixed points, as well as the fabrication and calibration of his thermometers, would require considerable facilities. His decision to borrow money to finance a workshop can be understood.

Table 1. Scales used for Fahrenheit's wine-spirit thermometers of 1707 and 1714. The temperatures of the fixed points are underlined.

t_F		t		
°F (1707)	°F (1714)	°C	Wolff (1714)	Fahrenheit (1724)
$\underline{90}$	$\underline{96}$	37	aestus intolerabilis	Extream Hott
60	80		calor ingens	
30	64		aer calidus	
0	48		aer temperatus	Temperate
$\underline{-30}$	$\underline{32}$	0	aer frigidus	
−60	16		frigus ingens	
$\underline{-90}$	$\underline{0}$	−20	frigus vehementissimum	Extream Cold

Both of Fahrenheit's scales described here – from 1707 and 1714 – are based on an alcohol-in-glass temperature. The scales contain the same three fixed points: the eutecticum of the $NaCl-H_2O$-system, the ice-point and the body-temperature. Table 1 compares those two scales with the Celsius scale and also includes the labelling given by Wolff [11] and later by Fahrenheit [18e].

2.4. The Quicksilver Thermometer

Origins. Fahrenheit [18a] learned from Amontons' [27] writings that the height of the mercury column in the barometer is influenced, albeit only slightly, by temperature, in that the column measured three "Paris Lines" higher in summer than in winter (1 ligne = 1/12 pouce = 2.256 mm). These observations inspired Fahrenheit to construct thermometers to measure the higher temperatures involved in the study of boiling phenomena: for this purpose he employed quicksilver as medium.

Fahrenheit produced his first quicksilver thermometers for his own use during 1713/14 in Berlin. He began commercial production in 1717/18 after his move to Amsterdam. He sent the first three quicksilver thermometers to Boerhave, s'Gravesande and Lambert ten Kate, and included with each a wine-spirit thermometer (letter No.14 from May 30th,1729) [8]. With this, Fahrenheit wanted to demonstrate the exact correspondence between the two types of instrument. This demonstration completely backfired, since during the next few months he received complaints from all three recipients that there were discrepancies of up to 6°F in the range between 0°F and 96°F. In his efforts to establish the causes of these discrepancies Fahrenheit made two fundamental discoveries:

1. The readings obtained from quicksilver thermometers are effected by their glass-type, since different types of glass display different characteristics of thermal expansion.
2. The boiling temperature of water and other liquids is dependent on the barometric reading – that is, on pressure.

Both of these phenomena were thoroughly investigated by Fahrenheit.

The thermal expansion of glass. When the thermal expansion of glass approaches the same order of magnitude as that of the thermometer liquid, then the relationship between liquid density, calibre, length of scale and liquid-volume stated in equation (1) clearly has to be modified; and this is necessary for the quicksilver-in-glass thermometer. In this case, the equation (1) remains valid if we substitute the absolute expansion of mercury $V_t/V_0 = (V_t/V_0)_{Hg}$ on the left side, by the relative expansion of mercury in glass, $(V_t/V_0)_{rel}$ which can be calculated from the equation

$$\left(\frac{V_t}{V_0}\right)_{rel} = \frac{(V_t/V_0)_{Hg}}{(V_t/V_0)_{gl}} \tag{2}$$

where $(V_t/V_0)_{gl}$ is the absolute expansion of glass of a specific type. An equation of this form was described by Fahrenheit in words (letter No.14) [8].

Fahrenheit examined in detail the relative expansion of quicksilver in vessels of various types of glass, since he saw the glass-type as the basis of the discrepancies in correspondence between his wine-spirit and quicksilver thermometers. He gives a quotient for this:

$$\frac{V(96°F)}{V(\ 0°F)} - 1 \tag{3}$$

It is, however, extremely unlikely that Fahrenheit cooled his system to 0°F for each set of measurements, particularly since the zero-point on the quicksilver scale had not yet been defined and, in any case, lies at a different position from the zero-point on the wine-spirit scale (that is, as measured in our reference Celsius scale). In a letter to Boerhave (No. 12) [8] he writes:

"I begin to count at zero, 32 degrees below the point between thawing and freezing, which as you know, one obtains by mixing water and ice."

The interpretation of this is that in reality he measured the quotient

$$\frac{V(96°F)}{V(32°F)} - 1 = \frac{V_{37}}{V_0} - 1 \tag{4}$$

and transformed this to the quotient of equation (3) (the indices are again the Celsius temperatures). From this one draws the conclusion that Fahrenheit no longer saw the zero-point as a fixed point on his quicksilver scale, but rather as a calculated temperature, 32 degrees on his scale below the ice-point. We have transcribed Fahrenheit's experimental values to the quotient of equation (4), so that they can be compared with today's values for an identical reference volume $V(32°F) = V_0$. Table 2 shows Fahrenheit's experimental values in chronological order. Also included for later reference are Fahrenheit's values for the boiling temperature of water in degrees Fahrenheit. Table 2 reveals remarkable variations in relative expansions between types of glass of the same provenance. These are not only to be explained as the consequence of experimental error, but also as reflecting the variability of the raw materials used by the glassworks, of which Fahrenheit himself complained. He comments upon his measurements as follows (letter No. 14) [8]: "The softer a glass and therefore the lower its melting-point, the more it expands". Applying the absolute expansion of mercury, the cubic expansion coefficients of the glass-types can be calculated, using equation (2). These calculated values compare well with our current values.

Dependence of the boiling temperature on pressure. In April 1723 Fahrenheit conducted experiments on the "elasticity" of steam under varying degrees of temperature (letter No.10) [8]. The glass apparatus built for this experiment is shown in fig. 5. The right hand cylinder contains water which, before the sealing of the cylinder, had been boiled for some time to remove all gas. The steam pressure above the water surface p_s is held in equilibrium by the quicksilver column h. The surroundings were about 15°C and the measured values are shown in table 3. The height h is given in "Paris lines" (1 ligne = 1/12 pouce = 2.256 mm). As table 2 shows, in 1723 Fahrenheit could have been using a quicksilver scale in which the boiling-point was about 205.5°F; he had already retracted his earlier value of 212°F in January 1719. This possibility would affect the evaluation of the steam pressure measurements. In order to test this hypothesis we have plotted (in fig. 6) the ten readings of table 3 on a t_F, t-diagram: the temperatures of table 3 given by Fahrenheit are used as the ordinate, but the ten measured steam pressures are given today's Celsius temperature values. The height h of the quicksilver column has been corrected for room-temperature, that is, multiplied by

$$(\rho_{15} / \rho_0)_{Hg} = 0.997271$$

Fahrenheit had assumed for his quicksilver thermometer (as he had for his wine-spirit thermometer) that there is a linear relationship between volume and temperature. This condition is basically fulfilled for quicksilver. For a Fahrenheit scale, where the ice-point is $32°F \triangleq 0°C$, and the body-temperature is $96°F \triangleq 37°C$, a linear extrapolation to the boiling-boint of water 100°C would give the following Fahrenheit temperature:

$$t_F' = 32°F + 100\ (96 - 32)°F/37 = 204.97°F \approx 205°F$$

The straight line a in fig. 6 illustrates this relationsip, whilst line b is valid for 212°F. The ten readings in this diagram are closer to the line a. For our calculations we have therefore used $t_F' = 206°F$ and this appears as °F(206) in table 3. Fig. 7 is a p,t – diagram showing a comparison of Fahrenheit's readings with our steam pressure curve. The correspondence is quite good. Fahrenheit goes further, showing that the values $p_S^{1/4}$ are proportional to the saturation temperatures t_s, and this is confirmed in fig. 8.

The dependence of the boiling – temperature on pressure is a fundamental thermodynamic relationship which extends far beyond thermometry. Fahrenheit was the first to concern himself with the thermodynamic properties of steam. The two left – hand columns of table 3 are probably the oldest steam table in the world. Fahrenheit recognized all the implications of the relationship between boiling – temperature and barometric pressure. He proposed the use of thermometers to establish not only the height of mountains and the depth of mine shafts, but also barometric pressure at sea, where the ship's movement makes the use of barometers difficult. For this he describes [18e] a hypsobarometer (fig. 9), a quicksilver thermometer with dual scales and a double function. The lower scale measures temperature between 0°F and 96°F, while the upper scale measures the boiling – temperatures. However, as can be seen in fig. 9, the scale may also be divided into inches of mercury, as for a barometer. It has not been established whether such a hypsometer was produced.

The scale of the quicksilver thermometer. There are many sources which indicate that Fahrenheit used the fixed points of the wine – spirit scale – the ice – point at 32°F and the body temperature at 96°F – for the calibration of the quicksilver thermometer. He no longer considered the zero – point (0°F) as a fixed point. A linear extrapolation, which is valid for quicksilver (although not for wine – spirit) gives the boiling – temperature $t_F' \approx 205°F$. This is clearly true for all glass – types. Nevertheless, in table 2 Fahrenheit repeatedly gives the value of the boiling – points of water as approximately $t_F' \approx 212°F$, our current value. How could this happen? When one considers Fahrenheit's results as shown in table 2, a possible explanation

Table 2. Relative expansion of mercury in different types of glass. Boiling – point of water t_F'.

Date	Provenance of the glass	$(V_{37} - V_0)/V_0$	t_F'(°F)
5. III .1715	Potsdam?	1/174	
12.XII.1718	Glass A	1/180.5	212.5
23. I .1719	Glass B	1/174.3	212 – 213 (212) 205.5
Phil.Trans.	30(1724)1 – 3		212
20. III .1729	Amsterdam Bohemia England	1/179.1 1/166.4 1/175.3	211
30. III .1729	Bohemia or Potsdam Thüringen England Amersfoort Amsterdam	1/170 1/170.1 1/175.1 1/179.1 1/181.9	
17. IV.1729			205 – 212
	Jena 16III	1/170.7	

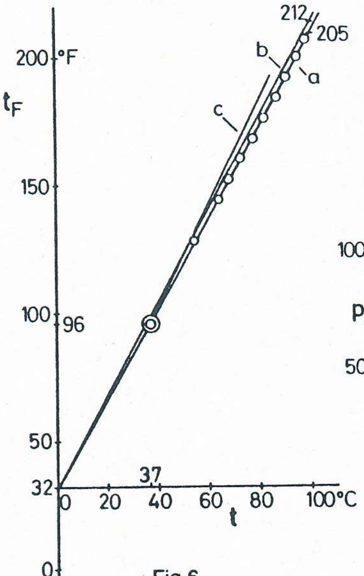

Fig.6

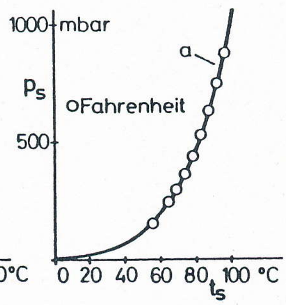

Fig.7

Fig.6: t_F, t – Diagram with Fahrenheit's measurements of steam pressure (circles); straight line a for t_F' = 205°F; line b for t_F' = 212°F; Curve c is an extrapolation of the wine – spirit scale.

Fig.7: Fahrenheit's values for steam pressure (circles) and today's saturation line a.

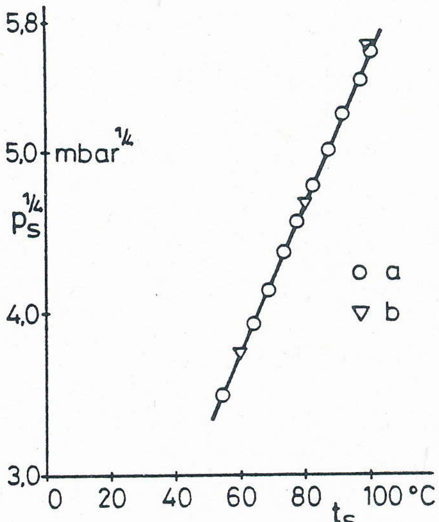

Fig.8

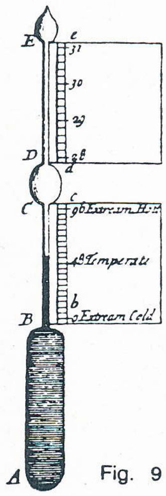

Fig. 9

Fig.8: $p_s^{1/4}$ as function of the saturation temperature t_s according to Fahrenheit. a Fahrenheit's values, b today's values.

Fig.9: Hypsobarometer according to Fahrenheit, 1724.

Table 3. Fahrenheit's steam table of 1723

t_F °F(206)	h lignes	p_s mbar	t_s °C	$p_s^{1/4}$ mbar$^{1/4}$
128	49 1/2	148.5	55.2	3.49
144	80 1/4	240.7	64.4	3.94
152	97 1/2	292.9	68.9	4.14
160	119	356.9	73.6	4.35
168	145 1/4	434.9	78.2	4.57
176	176	527.9	82.8	4.79
184	210 1/2	631.4	87.4	5.01
192	249 1/3	747.9	91.9	5.23
200	292 1/5	876.5	96.6	5.44
207	333 1/3	999.8	100.6	5.62

does however appear. After his move to Amsterdam he had begun anew with the fabrication of quicksilver thermometers and for this he measured the relative expansion of a glass A. At this point in time neither Fahrenheit nor anybody else, had yet recognized the influence of glass-type, so that he would have had no hesitation in using the measurements from glass A to produce a thermometer of glass B; and with this he could then have measured a boiling-temperature $t_F' = 212\ 1/2$ (which he mentions in the letter from December 12th, 1718, table 2). This hypothesis is supported by the following calculations:

$$t_F' = 32°F + \frac{180.5}{174.3}(205.5 - 32)°F = 211.7°F \approx 212°F$$

Fahrenheit seems to have sent three of the thermometers from this series, each accompanied by a wine-spirit thermometer, to his friends for testing (compare 2.4.).

These thermometers showed a body-temperature of about 98,6°F instead of the expected 96°F. Obviously Fahrenheit must have soon noticed this inaccuracy since within a few weeks he had notified them of a new relative expansion (this time, correctly for glass-type B) and a new boiling-point, 205,5°F instead of 212°F. The mention of the value 212-213 in the same letter must therefore refer to an earlier table.

In principle, it is impossible for wine-spirit and quicksilver thermometers to correspond other than at those common fixed points, where they are calibrated, since they define two different empirical temperatures. However, the differences are small as fig. 6 shows and might not have been noticed by his three friends had Fahrenheit not used a different glass-type.

So it appears that for some years he manufactured two different scales, and that this period was, at the very least, the ten years between 1719 and 1729. The fixed points of one scale were the ice-point at 32°F and the body-temperature at 96°F: for this, the boiling-temperature of water was at $t_F' \approx 205°F$. This scale was in all probability used primarily for those thermometers which extended only to about 96°F and were used for meteorological purposes. For scientific observations, however, particularly of boiling phenomena, Fahrenheit produced thermometers with a longer scale on which the boiling-point of water was at $t_F' \approx 212°F$. On this scale the body-temperature lost its use as a fixed point. The ice-point remained unaltered at 32°F.

Fahrenheit describes the further development of his quicksilver scale in letter No. 15, where he writes: "There are no points better defined than those of crushed ice, whose spaces are filled with sweet water, or of boiling water, but only as long as atmospheric pressure is taken into consideration. The temperature of 96 degrees can still be identified by calculation as I have done." This means that - from 1729 at the latest - he no longer used the body-temperature as a fixed point for those thermometers containing t_F'. For those quicksilver thermometers which extended only to 96°F, he probably continued to use the body-temperature for calibration.

Observations on Fahrenheit's quicksilver thermometers can be summarized as followed:

1. Fahrenheit was producing quicksilver thermometers experimentally in Berlin by 1713/14 and commercially in Amsterdam by 1717. He retained for a time the two fixed points of the wine-spirit scale, the ice-point at 32°F and the body-temperature at 96°F; that scale's zero-point he no longer considered a fixed point.
2. On such a scale the boiling-temperature of water would be $t_F' \approx 205°F$. Probably as a result of a change in the glass-type caused by his move from Berlin to Amsterdam, he measured $t_F' \approx 212°F$, a value which he soon corrected to 205,5°F, but which he, nevertheless, retained in the long run. After 1729 at the latest, he no longer used the body-temperature as a fixed point temperature, but retained only the ice-point and steam-point as fixed points. Those thermometers extending only to 96°F were an exception.
3. In his efforts to clarify the discrepancies between the readings of wine-spirit and quicksilver thermometers, he detected the influence of glass-type and the dependence on pressure of the boiling-temperature. He constructed a steam table for the saturation state with 10 measured points between 50°C and 100°C.

2.5. Concluding Remarks

1. Fahrenheit's particular service to thermometry lies in his use, even in the beginning, of reproducible fixed points for his thermometer scales. He must already have established this principle by the age of 20 or 21. Although others had used it before him (Newton, Amontons), it was not widespread. Fahrenheit was probably the first professional thermometer-maker who used it consistently.
2. Consequently, Fahrenheit was able to produce "corresponding weather-glasses" and through this, to end a long-running confusion in temperature measurement. Even an expert like Christian Wolff, who had recognized the significance of this correspondence, was unable to find the "trick" (the "artificium") which Fahrenheit described first in 1724.
3. His thermometers were considerably superior to those of his competitors and quickly achieved a widespread use - thereby also achieving a wide circulation and acceptance of his scale. The values of the fixed points (32 for the ice-point and 212 for the steam-point) are purely accidental. His fellowship of the Royal Society resulted in his thermometer, and thereby his scale, receiving particular acceptance in England and consequently later also in North America and the British Empire.
4. The accuracy of his thermometers allowed him to measure thermodynamic properties of liquids - for example, density, boiling temperature and thermal expansion (also relative to types of glass). He measured these parameters for many materials, and they were published as Tables. Of particular importance were his discoveries of the subcooling of water in the process of freezing and the dependence on pressure of boiling-temperature. He constructed the first steam table.
5. Thermodynamics could develop as a separate science only after the precise and accurate measurement of temperature had become possible. Fahrenheit made a considerable contribution to this and can therefore with justification be called a pioneer of exact thermometry.

Acknowledgements

The author wishes to thank the Director of the Deutsches Museum, Munich and the Director of the Museo di Storia della Scienza, Florence for their permission to reproduce fig. 1 and fig. 3 respectively. Also Mr. John Daborn and his wife for their translation from the German manuscript.

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4. Friedrich Albert Mayer: Daniel Gabriel Fahrenheit, Sein letztes Werk, Testament und Nachlaß. [His last project, last will and testament]. Technikgeschichte 33(1966) 160 – 181.

5. After Daniel Fahrenheit's death, his partner, Ulrich Isenhut, had to pay 21.000 Gulden as well as a considerable sum for real estate to the heirs (see 6).

6. Ernst Cohen u. W.A.T. Cohen – de Meester: Daniel Gabriel Fahrenheit. Verh. Kon. Akademie Wetenschappen Amsterdam, 1. Sect.16 (1936) No.2, 1 – 37. Second reference 40 (1937) No.8, 682 – 689 (here the application is repeated). See also Chemisch Weekblad 33(1936) No.24, 374 – 393 and 34(1937) No.45, 727 – 730.

7. Ole Roemer's "Adversaria". Edited by Thyra Eibe and Kirstine Meyer. 271 pages. Copenhagen 1910.

8. Pieter van der Star: Fahrenheit's letters to Leibniz and Boerhave. 195 pages. Leiden and Amsterdam 1983.

9. Horst Kant: Gabriel Daniel Fahrenheit, René – Antoine Ferchault de Réaumur, Anders Celsius. 133 pages. Leipzig: Teubner 1984.

10. Christian (after 1745, Baron) Wolff (also Wolf) (1679 – 1754), mathematician, philosopher and scholar of the Late – Enlightenment. In 1707 he became professor in Halle, but in 1723 he was relieved of his post for being a determinist and an enemy of religion by Friedrich Wilhelm I. In 1740 he was recalled to the chair of natural and human law by Friedrich the Great, and later became Chancellor of the University of Halle.

11. (Christian Wolff): Relatio de novo barometrorum et thermometrorum concordantium genere. Acta Eruditorum, Leipzig, August 1714, 380 – 381. "Acta Eruditorum" (roughly translated: "Reports of the Scholars") is the oldest scientific journal in the German language, and from 1682 edited by O. Mencke; published until 1782.

12. Gottfried Wilhelm Leibniz (1646 – 1716). Mathematician, scholar and philosopher of the Enlightenment; diplomatic and judicial activities, counsellor and historian in Hannover and Wolfenbüttel. In 1673 became a member of the Royal Society, and in 1700 founded and was the first president of the Societät der Wissenschaften zu Berlin (Society for Science in Berlin). Developed infinite calculus and the first modern calculator.

13. In this answer is a phrase which holds true for every inventor of a perpetuum mobile: "The only thing which remains is to destroy the state of equilibrium, through which the machine comes to rest (sed id unicum adhuc restare, ut equilibrium, quo machina ad quietem redigitur tollatur)."

14. Herman Boerhave (1668 – 1738), Professor of botany, medicine and chemistry in Leiden. Book: "Elementa Chemiae".

15. Wilhelmus Jakobus s'Gravesande (1688 – 1742), Professor of mathematics, astronomy and physics in Leiden. Wrote the first textbook on experimental physics in 1720 – 1721.

16. Petrus van Musschenbroek (1692 – 1761), pupil of Boerhave, 1719 Professor of mathemathics and physics in Duisburg, 1725 in Utrecht and 1740 in Leiden. He experimented with the "Leidener Flasche" (the Leiden jar).

17. Friedrich Albert Meyer: Fahrenheits Anteil an der Entdeckung des Platins. [Fahrenheit's contribution to the detection of platinum]. Z. Erzbergbau und Metallhüttenwesen 4 (1951) 221 – 222.

18. The titles translated from Latin are as follows:
a) Experiments on the boiling – points of some liquids. Phil. Trans. London 33 (1724) 1 – 3.
b) Experiments and observations on the freezing of water in vacuo. Phil. Trans. London 33 (1724) 78 – 84.
c) The specific weights of some bodies measured at different times for different purposes. Phil. Trans. London 33 (1724) 114 – 118.
d) Description and application of a new araeometer. Phil. Trans. London 33 (1724) 140 – 141.
e) Description of a new barometer. Phil. Trans. London 33 (1724) 179 – 180.

19. Abhandlungen über Thermometrie von Fahrenheit, Réaumur, Celsius. [Essays on the thermometry of Fahrenheit, Réaumur, Celsius]. Ed. A. J. v. Oettingen. 140 pages. Leipzig: Engelmann 1894.

20. Galileo Galilei (1564 – 1642). The invention of the thermoscope is passed on to us by his pupil V. Viviani (1622 – 1703).

21. Cornelius Jacobszoon Drebbel (1572 – 1634), born in Alkmar, creative inventor, philosopher and mathematician, lived also at the court of the German emperor Ferdinand II in Prague and of the English King James I in London. First submarine on the Thames.

22. For the history of thermometry other than those already mentioned the following may be quoted:
a) J. H. van Swinden: Dissertation sur la comparison des thermomètres. [Dissertation on the comparison of thermometers] Amsterdam 1778.
b) Johann Heinrich Lambert: Pyrometrie oder vom Maaße des Feuers und der Wärme. [Pyrometry or the measure of fire and heat]. Berlin 1779.
c) Fr. Burckhardt: Die wichtigsten Thermometer des 18. Jahrhunderts. [The most important thermometers of the 18th century] Bericht der Gewerbeschule zu Basel. 30 pages. Basel 1871.
d) E. Gerland: Das Thermometer. [The thermometer]. 48 pages. In: Sammlung gemeinverständlicher wissenschaftlicher Vorträge, ed. Rud. Virchow and v. Holtzendorff. XX. Serie, Volume 457 – 480. Berlin: Carl Habel 1885.
e) E. Gerland and F. Traumüller: Geschichte der physikalischen Experimentierkunst. [History of the art of physical experiments]. 442 pages. Leipzig 1899. Reprographical reprint Hildesheim 1965.
f) Kirstine Meyer: Die Entwicklung des Temperaturbegriffs im Laufe der Zeiten. [The development of the understanding of temperature through the years]. Braunschweig 1913.

23. M. Celeste Cantù a. M. Luisa Righini Bonelli: The Accademia del Cimento. 16 pages. Nardini Ed., Centro Intern. del Libro. No date.

24. Saggi di Naturali Esperienze fatte nell' Accademia del Cimento. Firenze 1667. Reprint Pisa: Domus Galilaeana 1957.

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28. N. Ernest Dorsey: Fahrenheit and Roemer. J. Washington Acad. Sciences 36 (1946) No. 11, 361 – 372.

29. The steam pressure of pure ethylalcohol at 100°C is 2.19 bar.