The hydrometer

Rømer's hydrostatic measurements

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The hydrometer (also called an aerometer) is an instrument which today is mostly used by home-brewers but which previously was an apparatus often used to determine the density of fluids. There are two main types of the instrument; the best known is the type in which the neck is supplied with a scale, so one can determine the density of a fluid, or other things which depend on it, ex. the alcoholic strength, by how low the weight sinks into it. However, on the other type there is one mark on the neck and a pan on top of the hydrometer; when one has to measure a density, the weight is lowered down into the fluid and a number of leads are placed on the pan until the weight has sunk down to the mark, which means that during all the measurements one displaces the same volume, and by using Archimedes' principle one comes to the conclusion that the relative density (water is fixed to 1) becomes $p=1+m/m_o$, where m is the weight of the leads on the scale and m_o is the weight of the empty instrument. In many places, Fahrenheit[1] gets the credit for having invented this type of hydrometer. He describes the instrument as new in his article *Arcæometri novi description & usus* (The description and usage of a new hydrometer), but after Ole Rømer[2]'s notebook was retrieved in the beginning of the last century, the credit must be assigned to him (today, a further development of the instrument is known as Nicholson's Hydrometer); Fahrenheit has probably seen Rømer's hydrometer during his visit in 1708, just as he during his visit also learned a lot about the production of thermometers[3].

The most serious problem connected to the calibration of the first type is that the top upper part where the scale is located has to have exactly the same diameter all over which is difficult to ensure. The least bit of imprecision will cause the instrument to give extremely erroneous results (unless one does not want big problems with the graduation of the units of the scale). The advantage connected to the Rømer instrument is the fact that it displaces the same amount of fluid and that imprecision therefore does not matter.

If then, on top of it all, it is possible to make an instrument, which precisely weighs 100 or 1000 times as much as one's standard leads, these could be used and the conversion to relative density would merely consist of counting the leads. The fact that it is exactly what Rømer is trying to do is shown below, although he does not succeed. The instrument does not sink low enough, but the problem is solved at the cost of the easy conversion.

The oldest stories about an apparatus of this kind derive from around the year 400 (Hypatia[4] in Alexandria), but they have apparently been forgotten. The next time an apparatus is mentioned is in Samuel Peppy's journal on December 9, 1668[5], where Boyle is displaying one: *and did give me a glass bubble, to try the strength of liquors with*. Robert Boyle himself refers to his apparatus in "*New Essay instrument*"[6], in which his article is really about how one easily determines if a gold coin is a fake. But he has the idea for the apparatus from a hydrometer which he had presented earlier; both the description of the apparatus and the present depiction show that it is the type which sinks more or less in the fluid depending on its density. He writes, among other things*: ….But afterwards considering this little Instrument somewhat more attentively, I thought the application of it might easily be as 'twere inverted, and that, whereas 'twas employed but to discover the differing Gravities of several Liquors, by its various degrees of Immersion of them…*

Rømer was already occupied with hydrometers during his stay in Paris, which is shown in a letter[7] from John Locke to Nicolas Toinard (sent in 1679), in which it says: *Therefore, the Rømer hydrometer, which they have had made for me, has all the properties, which can make a thing highly treasured.*

Rømer's brine measurement

The paragraph[8] about the concentration of brine focuses on how one can measure how many lod[9] of salt per pot[10] of water there is in a brine given. Rømer assigns an instrument (a hydrometer with a pan) to measure the concentration of salt, along with a table so one, from a measured value, can determine this. There are three tables in this paragraph, only one of the two first has been measured, but which one?

The first table indicates how much a brine weighs in comparison to the weight of the same amount of water, if the weight is set to 1000. it could have been measured by weighing out 1000 ort of water (barely a pot) in a flask and placing a mark on it thus when a brine with a known concentration (lod of salt per pot) was mixed it could be filled to the mark and the added weight could be directly measured with the accuracy of 1/16 ort (his smallest leads[11]). The numerical values are in compliance with the modern measurements.

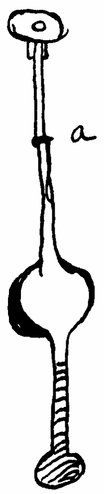
The second table indicates how much extra-weight one has to place on the hydrometer when it is sunk into different brines in order for it to sink to a mark on it. The numbers are given with the accuracy of 0.01 unit weight, and when one takes into account that the unit for the overweight is approximately 0.06 g (0.01x0.206[12]x29 9/16 g (see later)) the accuracy of the numerical indications is impossible to obtain through a direct measurement, and a different explanation to the table has to be found.

Thus, we have to conclude that Rømer has only measured the values in the first table because he could; the second table is an aid table which has been calculated and which leads to the last table, which is the one that is supposed to be used in practice.

After having made the first table, he notices that the relative density of a brine does not increase linearly with the amount of salt; there are a couple of measurements on the basis of this strange relationship, as well as an attempt to explain[13] it. Rømer imagines that the salt penetrates into the pores of the water.

The hydrometer

Here comes a description of the instrument, which consists of a small container, possibly glass, in which something heavy is placed at the bottom (lead or mercury?). The weight is 26 15/16 As; it is strange how sixteenths are used since his lightest ort lead weighed 1/16 ort = 0.3 As. On top of the container, a small pan is placed (made of brass or lead?, it could be that plumbea means equipped with a seal, since it would be appropriate), which brings the collected weight to 29 9/16 As; the leads he has to use on the scale to make the apparatus sink into a brine has the unit of 1/100 of this weight. Apparently, the unit for his overweight does not fit his regular leads.



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cum corona $29\frac{9}{16}$ seu 29.562—

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≠ adest præterea pondus pro aqva simplici 12.35

From Adversaria but changed a little so it is in better accordance with the original

The weight of the apparatus is more comprehensible if it is converted into ort (here, his first measured value[14] is used, 1 pound = 2425.12 As.). The result is that 26 15/16 As. = 5 11/16 ort (the difference is below 0.01 %). Now the pan is added and the total weight becomes 29 9/16 As. = 6 ¼ ort = 100/16 ort (the difference is approximately 0.14 %). The unit of overweight thus becomes his smallest leads of 1/16 ort.

He discovered that the apparatus did not sink down low enough in pure water. A permanent overweight had to be added, so about half of the neck was covered, marked **a**. He had the overweight leads they did not change, and he found the overweight necessary in connection to the weight of the apparatus. This overweight was found to be 12.35 units. Next to the drawing of the hydrometer, we find a list of numbers, which can be interpreted as follows: A suitable overweight is found to 10” (inches)[15] of a thread (copper?), because thread can be pulled in very similar and small diameter. The apparatus with the pan is weighed with the same thread and the total weight is 91” (all the numbers are added up, 2.2 and 1.1 is to be read as 2”2 double lines and 1”1 double lines, 1 double line = 1/6”). Included in the total weight is the 81” thread for the instrument with no overweight, and if 81” is supposed to equal 100 units, the 10” will equal 12.35 units. Of course, the interpretation of the numbers is not certain but rather a proposal. The numbers are listed in a peculiar way and it is difficult to see if they are supposed to have a different purpose than to determine the overweight.

New instrument of the same type

It was now possible for Rømer to work out the second table by using Archimedes' prinicible. If we name the relative weights from table one **d**, the overweight that is to be laid on the hydrometer will be:

$$p = 112.35 \times (d-1000)/1000$$

In this way table two is worked out (**p** is stated with two decimals).

Empirically, he now found a connection between p and the number of lod salt per pot of water **c**. Rømer explains the connection by using words and logarithms:

$$\log p = \log 1.38 + (1-1/20-1/300) \times \log c$$

Through interpolation and calculations, he was now able to find the last table in the paragraph, in which there for integral values of p (1/16 ort) is indicated how many lod and qvints of salt there are per pot of water in the given brine. Next to the table, we find some “secret” writing[16], which indicates that he wanted to keep the construction of the hydrometer a secret, which might also be the reason why he stated the weight in As.

Thus, after having thought out and constructed the hydrometer, Rømer has measured the relative weight of a number of brines in relation to water. On this basis, he works out a table, so the apparatus can be used for future measurements of the quality of brines.

Other measurements and a conclusion

This is where the paragraph on brines ends with the description of some other experiments, during which he notices, among other things, that a sugar solution in water can be diluted to half the concentration, which corresponds to half of the overweight, contrary to what he discovered during the tests with salt water. And Rømer concludes:
Thus it is proven that if a pot of salt or sea water is diluted with a pot of fresh water, it does not add up to a mixture of two pots.

Apparently, the fact that 1+1 does not always equal 2 has puzzled him.

The measurement of alloys

An example of how Rømer arranged an instruction in a technique so even unlettered people could measure important sizes can be read in the notes[17]. It is a description of how one, in a simple way, can find the composition of alloys and other mixtures.
The theory behind this paragraph is as follows: let there be given c parts by weight of a mixture, which consists of the substances A and B; in the mixture, is a parts of A and c-a parts of B. When the mixture is sunk into water, q_c parts is lost in weight; c parts of A and B loses q_a and q_b parts respectively in water. From this, the relative density of the alloy, of A and B, is determined (in relation to water), which leads to $\mathbf{a/(c-a) = (q_b-q_c)/(q_c-q_a)}$ or $\mathbf{a/c = (q_b-q_c)/q_b-q_a)}$
If A is gold, one is interested in the number of weight units A per 24 weight units of the alloy, and it becomes as follows:
The carat weight = 24 x $(q_b-q_c)/(q_b-q_a)$
In regards to the use of the method, an example is given: 855 parts by weight of gold-copper. The alloy loses 55 parts by weight in the water; 855/19 (the density of gold in relation to water) = 45; 855/9 (the density of copper in relation to water) = 95; from this the carat weight = 24 x (95-55)/(95-45) = 19 1/5 carats.

To make the method even easier to use, since division, at that time, was found to be extremely difficult for regular people, a table was set up in which the density is set at 19.16, 10.45, and 8.96 for gold, silver, and copper, respectively; the weight quantity of the alloy is set at 100000. From one simple measurement of the weight loss in the water, as well as knowledge of what metals are included, the carat weight can be determined; another table has also been given, so the quality (measured in sixteenths) can be determined in a silver-copper alloy. Then, a big table is given[18], which can be used if the mixed metal is an alloy of silver and copper, although one has to know the relation between the two; he mentions how this can be estimated from the colour.

In a completely different paragraph in the notes[19], Rømer takes the matter up again, in which he gives a graphic method for the determination, so the work of measuring is minimized further. The method can also be used if one part of the mixture is lighter than water; there is an example in which lead is mixed with wax and wood[20].

References

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The internet: http://www.pepys.info/1668/1668dec.html

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Thyra Eibe and Kirstine Meyer 1910: *Ole Rømers Adversaria*. København. The original is at the Royal Library, Copenhagen.

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[1] Fahrenheit is talking about his instrument in *"Philosophical Transactions"*, 1724, vol. 33, pp. 140.
[2] Ole Rømer 1644-1710.
[3] Friedrichsen og Torzen 2004, pp. 265.
[4] Alic, M., 1986.
[5] http://www.pepys.info/1668/1668dec.html
[6] *"Philosophical Transactions"*, June, 1675. Picture in figure 8.
[7] Friedrichsen og Torzen 2000, pp. 587.
[8] Thyra Eibe og Kirstine Meyer 1910, pp. 7.

[9] The fundamental unit is one foot[15]. 1 pound = 2 marks = 16 ounces = 32 lod = 128 qvints = 512 orts = 1/62 of the water weight of the cubic foot = 499.75 g.
[10] 1 pot = 1/32 cubic feet = 968.120 cubic centimeters.
[11] Thyra Eibe og Kirstine Meyer 1910, pp. 197. Also see Andreas Nissen 1944.
[12] 1 As = 206 mg (Amsterdam carat)
[13] Thyra Eibe og Kirstine Meyer 1910, pp. 11.
[14] Thyra Eibe og Kirstine Meyer 1910, pp. 197.
[15] 1 foot = 12 inches = 144 lines = 314.07 millimeters.
[16] Claus Thykier 1989. It should be noticed that in this writing there are some strange repetitions. At the examination of the original document, it appeared that only the top "secret" line was written with the same pen as the rest of the document. The two lines below mostly recall that of a copy (for fun, a test?), and they are written with a handwriting similar to the numbering of the folio sheets. It says "prescribed use".
[17] Thyra Eibe og Kirstine Meyer 1910, pp. 13.
[18] Thyra Eibe og Kirstine Meyer 1910, pp. 16.
[19] Thyra Eibe og Kirstine Meyer 1910, pp. 198.
[20] Thyra Eibe og Kirstine Meyer 1910, pp. 201.