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Galileo Chain Thermometer

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Abstract
This relatively rare thermometer has a rather unusual display: lower temperatures are located at the top of the scale, higher ones at the bottom. A sphere on a chain floats in a suitable liquid, sinking at high temperatures when the density of the liquid decreases and rising in the increased density at low temperatures. With reasonable effort and experimental dexterity, you can construct this thermometer yourself using ordinary materials.

Galileo thermometers, with a pre-determined number of coloured spheres floating in a usually high cylindrical container, are well-known and widely used. Each of the spheres is marked with a different number indicating the temperature at defined intervals. Intermediate temperatures cannot be read. It could actually be called a very early digital thermometer [1].

The so-called Galileo thermometer with a chain has only ***one*** measuring sphere in the liquid. The form of the sphere can be similar to the ones in a normal Galileo thermometer (figure 1), but may also have a different shape. ***One*** chain, with its end set down on the bottom, hangs down from the sphere and is a bit longer than the measurement cylinder. There is an analogous temperature scale on the cylinder, but the measurement scale is just the opposite of the usual form: higher temperatures are marked at the bottom of the scale, lower ones at the top. This unusual kind of graduation can easily lead to incorrect reading of the temperature since the scale normally shows higher temperatures at the top.

This kind of thermometer is definitely not a Galileo thermometer in the usual sense. In German, it is fittingly called a chain thermometer (Kettenthermometer). In English-speaking areas, if it is even available, it is simply called a Galileo thermometer [1, 5]. In order to differentiate it from normal Galileo thermometers, we call it a *Galileo chain thermometer* for three reasons: it is based on the same measurement principle of dependency on the density of the temperature, the floating spheres look similar and the chain is the characteristic feature.

Figure 1. A prototype of a Galileo chain thermometer with **one** floating measurement bob (filled with a red liquid) attached to a chain hanging from it. Overall size: 41 cm.

Figure 1 shows a prototype of the very first Galileo chain thermometer, which was invented in the German company Moeller-

Sommer-Therm [2] by the engineer Hans-Juergen Fiedler at the beginning of the 1990s. This model, however, was never sold commercially.

In its place, two additional variations of the Galileo chain thermometer were patented at the German Patent Office in 1995 and 2002 [3, 4; figure 2].

The version on the left [3] has two chains attached to the measuring sphere as well as to the opposite sides of the inner wall of the cylinder. These centre the measuring sphere in the middle of the container. The version on the right [4] has two free-floating spheres in a container. One of the spheres floats on the surface, while the other – the measuring sphere – exhibits varying elevations according to the temperature, dragging the chain in varying lengths along with it. Both of these versions eliminate a disadvantage of the simple Galileo chain thermometer, namely that the chain lying on the bottom could pile up in one place and become entangled, thus leading to a falsified display.

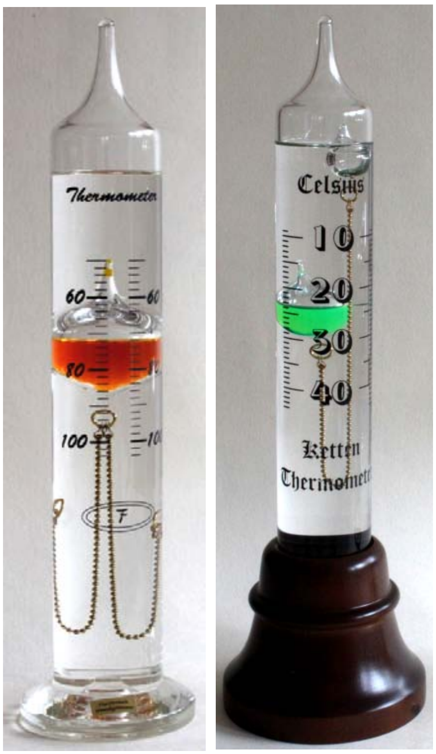

Figure 2. Two additional Galileo chain thermometers.

These two versions were sold with Fahrenheit and Celsius scales until around 2004.

Only one company [5] on the Internet offers this kind of thermometer, one which corresponds to version [3].

Like the original Galileo thermometer, this version also needs a good hour to adjust to a sudden change in temperature and enable a useful reading of the temperature. This fact makes it a more decorative element than a quickly readable instrument.

Construction

Let us examine the construction of the prototype, the easiest version to recreate. Attached to the bottom part of the measuring sphere floating under the surface of the liquid, there is a thin, flexible, sufficiently long chain with a density greater than that of the liquid. The end of the chain lies loosely at the bottom of the container. As the temperature rises, the density of the liquid decreases, making the measuring sphere sink and place as many chain links on the bottom of the container as it takes for buoyancy force and weight force to be back in equilibrium. As for the normal Galileo thermometer, liquids with high cubic expansion coefficients are used, and their composition is kept secret by the producers. Research in patent data banks has resulted in diverse indications for suitable liquids, all of which, however, are either only described or can only be bought in unattractively large amounts.

In principle, a rather similar effect can be seen in children's helium-filled balloons attached to a sufficiently long string. The helium balloon keeps rising until the increasing weight of the longer and longer string compensates for the buoyancy. However, the helium diffusing steadily from the balloon causes it to sink continuously, which makes a helium balloon unsuitable for measuring temperatures.

The Physics of the Galileo Chain Thermometer

A mathematical analysis can indicate suitable materials for the construction of a Galileo chain thermometer. Let V_K be the volume and m_K the mass of the floating measuring sphere, ρ_F the density of the liquid and h the length of the chain from its suspension point on the measuring sphere to the lowest point of the hanging chain. In each respective equilibrium state, the mass of the displaced liquid $V_K \cdot \rho_F$ must correspond to the mass of the measuring sphere m_K *and* to the mass of the hanging chain down to its lowest point. With d_{chain} as the mass of the chain per length ($d_{chain} = m_{chain} / l_{chain}$), we get

$$V_K \cdot \rho_F(T) = m_K + d_{chain} \cdot h \qquad (1)$$

Consequently

$$h = \left(V_K \cdot \rho_F(T) - m_K\right) / d_{chain} \qquad (2)$$

With two different temperatures T_1 *and* T_2 the result is a difference in the length Δh of the chain and also in the height of the measuring sphere, because both are connected directly

$$\Delta h = V_K \cdot (\rho_F(T_2) - \rho_F(T_1)) / d_{chain} \qquad (3)$$

The interpretation of the equation is that the greater the volume V_K of the measuring sphere and the difference in density at the varying temperatures T_1 and T_2 and the smaller the value of d_{chain} become, the greater Δh becomes. Δh does not depend on the mass of the measuring sphere, but the suspension height h does indeed.

The volume of the chain has been disregarded here since it is very small in relation to the volume of the measuring sphere (<1.5%).

Example: Let us choose water as the liquid [6]. Let the measuring sphere have a volume of V_K = 30 cm^3; let the chain weight be about $d_{chain} \sim 0.1$ g/cm. With equation (3), the result for the drop of the sphere at a change in temperature from 20°C to 30°C (with water ρ_W(20°C) = 0.9982 g/cm^3; ρ_W(30°C) = 0.99564 g/cm^3) is:

$$\Delta h = 30\, cm^3 \cdot (0.99564 \;\; g/cm^3 - 0.9982 \;\; g/cm^3) / 0.1\, g/cm = -0.77\, cm\,.$$

This is a very slight drop, which demonstrates that water is not very suitable. In addition, water has a clearly non-linear change in density in respect to temperature, which is why the reading scale would also turn out to be non-linear.

Preparatory Measurements for Construction of a Galileo Chain Thermometer

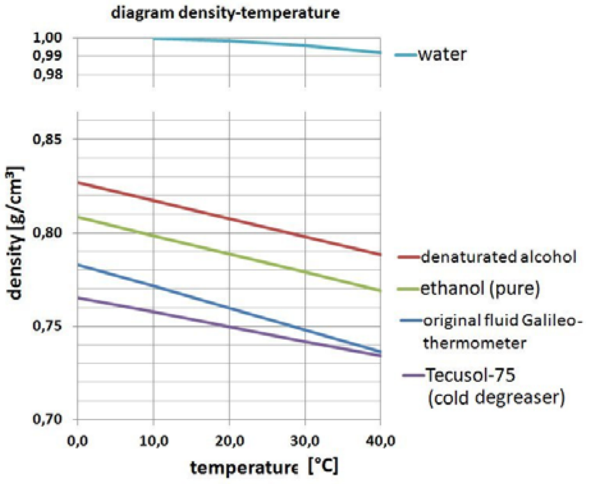

Figure 3. Density-Temperature Diagram for diverse liquids.

We have measured the density of diverse liquids depending upon temperature by an areometer or used data from the Internet (figure 3). At the top of figure 3, the non-linear, weak dependency of water subject to the temperature is shown. Beneath this, the corresponding dependencies of denaturated alcohol, pure ethanol, the original liquid from a broken Galileo thermometer and Tecusol-75 [7] (cold degreaser) are displayed. Within the temperature range from 0°C to 40°C, these liquids demonstrate a very good linear behaviour. The greater the slope of the line, the more suitable the liquid is for this kind of thermometer. Denaturated alcohol is easily obtainable. It demonstrates a slightly lower slope than pure alcohol, which may have to do with the additives in denatured alcohol. Moreover, alcohol is hygroscopic and actually always contains some water. The original liquid from a Galileo thermometer is somewhat better than denatured alcohol – but unfortunately cannot be purchased directly. Cold degreaser is an insider-tip from a producer of Galileo thermometers. Tecusol-75 proved to be even less suitable than denatured alcohol. Additional possible liquids (methanol, petroleum, carbon tetrachloride) have not been examined by us. In the following realisation, denatured alcohol is used.

The slopes of the lines for the liquids in figure 3 are:
$\gamma_{DA} = -9.58\cdot10^{-4}$ g/cm³K ; $\gamma_E = -9.78\cdot10^{-4}$ g/cm³K ; $\gamma_G = -11.67\cdot10^{-4}$ g/cm³K ; $\gamma_T = -7.80\cdot10^{-4}$ g/cm³K

Experimental Realisation

For the following experiments, it is helpful to have a scale which can weigh 0.1 g as well as a measurement cylinder capable of determining volumes of 1 cm³ or, even better, 0.5 cm³. An electronic thermometer with a fairly long measuring tip is also useful for calibration.

Various small containers are available for use as the measuring sphere, for example, a plastic measuring sphere from a defective original Galileo thermometer ($V_K \sim 9.5$ cm³; $m_K \sim 6.9$ g; figure 4), a small plastic screw-cap shampoo bottle ($V_K \sim 30$ cm³; $m_{Kempty} \sim 14$ g) and a plastic earplug box ($V_K \sim 15$ cm³; $m_{Kempty} \sim 3.7$ g). You also need a silver chain with a length of l = 50.0 cm and a mass of m = 1.70 g. There are no limits to your creativity in regard to finding suitable containers and chains.

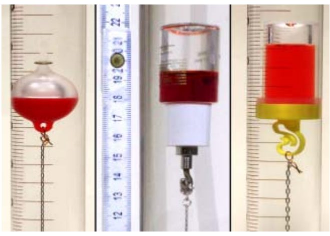

Figure 4. A sphere from a defective Galileo thermometer (left); a little plastic bottle (shampoo) with a magnetic holder (middle); a plastic earplug box (right).

For the mass per length of chain we get: $d_{chain} = 1.70/50.0\ g/cm = 0.0340\ g/cm$.

If the measuring sphere should cover a temperature range from 10 °C to 30 °C (ΔT = 20 K), the equation (3) for denatured alcohol results in:

$$\Delta h\,(20\,K) = V_K \cdot \gamma_{\mathrm{DA}} \cdot \Delta \mathrm{T} / d_{chain} = 9.5\,cm^3 \cdot 9.58 \cdot 10^{-4}\,g/cm^3K \cdot 20K / 0.034\,g/cm = 5.4\,cm$$

The cylindrical measurement container should thus be at least 20 cm high, or even better 30 cm to 40 cm high. With a suitable measuring cylinder, the temperatures can be read easily since 10 ml on the scale equal exactly 1 cm.

The chain is attached to the measuring sphere. For the example of the Galileo sphere, the mass of the measuring sphere can be optimized with an additional weight of 0.315 g (flat brass washer). With this, the measuring sphere floats in the denatured alcohol at a temperature of 20°C at an approximate height of 19 cm above the bottom, regardless of how much liquid is still above it. Equation (2) helps to calculate the effect which a small additional mass Δm_K = 0.1 g added to the measuring sphere has upon the floating height h: $\Delta h = \Delta m_K / d_{chain} = 0.1g / 0.034\,g/cm \approx 3\,cm$. This demonstrates how sensitively the floating height h reacts to the smallest of changes.

The little plastic container with a screw cap (V_K = 30 cm³, m_{empty} ~ 14 g; figure 4, middle) is first filled with approximately 25°C coloured water (~10 ml) until it floats just at the surface of the container filled with denatured alcohol. At this time, it has a mass of approximately 24 g (~30 cm³·0.8 g/cm³). The coloured water allows the level of the liquid to be read easily, even with an unbalanced floating container. A small magnet with a holder is adhered to the screw-cap and attached to the silver chain, which hangs down from it.

Figure 5. Calibration of the system with an additional little measuring container. Temperature ~ 32 °C.

By very finely dosing addition (or depletion) of water into or from the small container or by adding/taking away small weights, the mass can be attuned very exactly. You continue doing this until the little container floats approximately in the middle of the cylinder at 20°C. You proceed in the same way with the other little measuring containers.

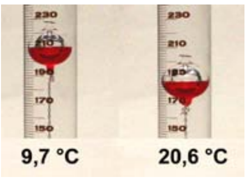

Figure 6. Final calibration of the chain thermometer (left 9.7 °C = 210 ml; right 20.6 °C = 186 ml; Δh = 2,4 cm).

The thermometer is calibrated by marking the position of the little measuring container at different temperatures. This can be accomplished with an additional, larger container which partially encompasses the actual measurement cylinder (figure 5). Warm or cold water (possibly with ice cubes) can be added. It is also lots of fun to warm up the Galileo thermometer with your hands, and, within limits, this can be done for calibration, too, but is pretty time-consuming. We want to emphasize once again that you must always wait for temperature equilibrium in order to attain a meaningful measurement.

Effective calibration results in $\Delta h_{\text{measured}}$ (10.9 K) = 2.4 cm (figure 6). This is ***not*** very consistent with the calculation ($\Delta h_{\text{calculated}}$ (10.9 K) = 2.9 cm) due to the slope in the temperature-density-lines for denatured alcohol from figure 3. There are several reasons for this: uncertainties in the measurement of the volume of the little measuring container, not taking the volume of the chain into account, not waiting long enough for temperature equilibrium, friction between the little measuring container and the inner surface of the cylinder, leakage of the little measuring container, evaporation of the denatured alcohol or accuracy of the reference thermometer, to name a few. Discussion of possible causes and their effect are very interesting and instructive from a physical point of view.

The final measurement is decisive for calibration! Even the producers of Galileo chain thermometers– and also normal Galileo thermometers – proceed in the same manner for their production. Now you only need to affix a temperature scale in Fahrenheit (°F) or Celsius (°C) onto the measurement cylinder (figure 7).

Incidentally, the Galileo chain thermometer from figure 1 has a difference in height of Δh (20 K) = 9.6 cm and measures the temperature clearly more sensitively. However, the other little measuring containers from figure 4 exhibit similar values since they have a greater volume.

Figure 7. Self-construction of the chain thermometer with calibrated Celsius scale.

In appreciation:
I (CU) would expressly like to thank my wife for her kind loan of diverse little bottles, a silver chain, a cylindrical glass vase and other utensils from our kitchen, all of which are intact and of further use!

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[2] The company's name is now moeller-therm; www.moeller-therm.de

[3] Utility patent DE000029511467U1, November 2, 1995: Galileisches Thermometer (mit einem Schwimmkörper und zwei Ketten). Galilei thermometer with a floating measuring container and two chains.

[4] Patent application DE000010050144A1, April 18, 2002: Galileisches Thermometer mit einem einzigen Festkörper zur Anzeige der Temperatur (mit einer Kette und zwei Schwimmkörpern). Galilei thermometer with one solid body for temperature display, with one chain and two little floating containers.

[5] The Taiwanese company River City Clocks offers a sort of Galileo chain thermometer in its assortment; www.rivercityclocks.com/index.php?route=product/category&path=18

[6] H. J. Schlichting, C. Ucke, Physikalische Spielereien, Verlag Wiley-VCH, Weinheim **2016**, 104.

[7] www.tecum-gmbh.de/en/products/surface-treatments/tecusol-75/