2. Mechanical Temperature Sensors

When one hears the word ‘sensor’, it is common to think of devices that deliver their measurements in the form of an electronic signal that can either be immediately displayed or subjected to subsequent processing and interpretation. Temperature measurement, however, has been a long-standing need, predating the development of electronic devices by centuries. In the absence of electronics, early temperature sensors were based on the mechanical effects of temperature - typically thermal expansion. While the mechanical temperature sensing technologies described in this chapter are decades or centuries old, they are still in widespread use because they meet the needs of many common applications in a reliable and cost-effective manner.

2.1. Liquid-in-Glass Thermometer

Although nearly three hundred years old, the ‘thermometer’ (more properly called a ‘liquid-in-glass thermometer’) is still a common fixture in numerous applications ranging from measuring a sick patient’s temperature to measuring the temperature of a pot of molten candy.

The basis of the thermometer’s operation is the thermal expansion of a working fluid. The volume of a liquid will change as a function of temperature. In general, as the temperature of a sample of liquid increases, that sample’s volume will also increase.

The relative change in volume versus change in temperature for most liquids is relatively small, typically characterized in hundreds of part-per-million per degree C, and referred to as the liquid’s Coefficient of Thermal Expansion (CTE). The change in volume of a liquid (ΔV) for a small change in temperature (ΔT) can be described by

$$\Delta V = V_0 \cdot CTE \cdot \Delta T$$

where V_0 is the liquid’s initial volume. Because a liquid’s CTE varies as a function of temperature, its volume is not a linear function of temperature.

Because most liquids’ CTE‘s are small (on the order of $10^{-4}/°C$, it is generally impractical to fill a tube of uniform cross section (such as a graduated cylinder) with liquid and use this arrangement as a thermometer. To observe small changes in volume requires the combination of a relatively large reservoir of working fluid connected to a long, thin capillary tube. This combination results in the familiar thermometer form of Figure 2.1.

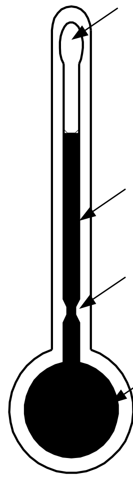

Figure 2.1 - Liquid Thermometer

Because the total reservoir's volume is much greater than that of the capillary tube, a small change in the total working fluid volume will result in a large change in the level of liquid in the capillary. For example, consider the case where the reservoir has 50 times the volume of the capillary. If the liquid's volume expands by just 1% (roughly the expansion experienced by mercury over a 55C temperature change), this will be sufficient to move the fluid level halfway up the capillary. By controlling the ratio of capillary volume to reservoir volume it is possible to control the thermometer's sensitivity.

If the working fluid's volume increases too much, however, there is the danger that the thermometer could burst. As most liquids are essentially 'incompressible', they are capable of exerting tremendous pressures on their containers when they expand, an effect often seen by unfortunate homeowners when freezing water bursts pipes during cold weather. For this reason thermometers often incorporate an expansion chamber at the top of the fluid column. If the working fluid expands beyond the length of the capillary, it can overflow into the expansion chamber. By making the volume of the expansion chamber large in relation to that of the capillary, one provides a margin of safety in terms of the maximum temperature the thermometer may be exposed to before it is damaged.

Another feature on many thermometers is the 'immersion line'. As most of the expansion effects result from the working fluid in the bulb, it is important that this fluid be exposed to a uniform temperature. For example, if one attempts to take a measurement by contact with just the bottom of the bulb, the temperature within the bulb's working fluid is almost certain to vary - resulting in measurement error. By defining the portion of the thermometer which must be exposed to the temperature being measured, a defined immersion line is an important aid in making repeatable measurements.

In certain applications it is desirable to be able to record the peak temperature that occurred. One such case is when a doctor or nurse measures a patient's body temperature. A peak temperature reading is desirable because when the thermometer is removed from the patient to be read, it will rapidly cool, potentially resulting in measurement errors.

One way of implementing a peak-reading thermometer is to make a constriction in the capillary between the reservoir and the scale. When the working fluid contracts as the thermometer cools, the constriction allows the column of working fluid to break, maintaining an indication of the maximum temperature. In most thermometers, a break in the working fluid column is a major problem. In a peak-reading thermometer, the break allows the working fluid in the capillary to remain at its peak excursion. To take another measurement, however, requires that one force the working fluid trapped above the constriction down so that it rejoins the fluid in the reservoir. This is typically accomplished by ‘shaking down’ the thermometer.

Although virtually every liquid experiences changes in volume in response to temperature changes, not all are desirable for use as working fluids in thermometers. The suitability of a working fluid also is dependent on the application for which the thermometer is intended. Some important characteristics of potential working fluids are:

Melting Point - A thermometer becomes ineffective and may be damaged at temperatures below which the working fluid freezes.

Boiling Point - A thermometer also becomes ineffective and may be damaged at temperatures above which the working fluid begins to boil and become a gas.

Magnitude of CTE - A high thermal expansion coefficient means a large change in volume versus change in temperature. This can makes it easier to make highly sensitive thermometers.

Consistency of CTE - While a large CTE can be useful, it is also important that it be consistent over the temperature range of interest. A CTE that is relatively constant over a wide temperature range makes it possible to use a capillary of constant cross section and a scale with a uniform spacing. While CTE varies as a function of temperature, some materials show more variability than others. It is possible to realize thermometers using working fluids with a highly variable CTEs, but using a material with less variability results in a simpler design.

Table 2.1 shows key characteristics of a number of potential working fluids. Note that water, although inexpensive and readily available is not commonly used as a working fluid as it has a high melting point, and significant variation in its CTE over a modest temperature range.

Table 2.1 - Thermal Characteristics of Selected Liquids

Material	Melting Point °C	Boiling Point °C	Coefficient of Thermal Expansion (10^{-6}/°C)
Water	0	100	207 @ 20C 640 @ 80C
Mercury	-39	357	182 @ 20C
Ethanol	-114	78	750 @ 20C
Methanol	-98	65	1198 @ 20C
Galinstan	-19	>1300	n/a

In applications such as consumer window thermometers, where a high degree of accuracy is not very important, organic working fluids such as alcohols have been popular because they are inexpensive and can be dyed to make the liquid columns easy to see. For more exacting applications that may require accurate measurements or measurements over a wider temperature range, mercury has traditionally been the working fluid of choice. Mercury's combination of low melting point, high boiling point, and consistent CTE over a wide range of working temperatures make it suitable for many thermometric applications. One major drawback of mercury, however, is its toxicity. For this reason, alternatives such as Galinstan (a trademark of Geratherm Medical AG) have been developed. Like mercury, Galinstan is a metallic material that is liquid at room temperature. Unlike mercury, which is an elemental metal, Galinstan is an alloy of gallium, indium and tin. Galinstan's melting point of -19C, although higher than that of mercury (-39C) still makes it useful for many thermometric application in which mercury is currently employed. The primary advantage of Galinstan over mercury is that Galinstan's component metals all have much lower levels of toxicity than mercury. For this reason a major application for Galinstan is in medical diagnostic thermometers where one does not want to risk exposing patients or clinical staff to mercury in the event that a thermometer should break.

2.2. Gas Thermometer

Like liquids, gasses also experience changes in mechanical properties in response to changes in temperature. Unlike a liquid, a gas has no fixed volume and will expand to fill whatever container is holding it. When a gas is confined to a fixed volume, however, its pressure will increase in response to increasing temperature, or decrease in response to decreasing temperature. This effect can be readily observed by putting an empty, but sealed plastic soda or water bottle in the refrigerator. As the air inside cools, the volume of the bottle shrinks because the internal pressure drops.

While the coefficient of thermal expansion for a liquid is highly dependent on that particular liquid, the relationship between pressure and temperature for a gas is largely independent of the particular gas in question. The behavior of most gasses conforms substantially to the *ideal gas law*:

$$PV = nRT$$

Where P is the pressure (Pa), V is the volume (m3), n is the number of moles of gas, R is the gas constant (8.314 Pa*m3/mole*K), and T is the absolute temperature (K). If one solves for P, it becomes clear that pressure is a linear function of absolute temperature, and that pressure becomes zero at absolute zero.

An important feature of the ideal gas law is that it doesn't require any special constants that are dependent on the exact nature of the gas, and the relation is substantially linear over a wide temperature range. This is significantly different than the case of thermal expansion in liquids, in which the applicable CTEs vary considerably both as a function of a liquid's composition and temperature.

The key to exploiting the ideal gas law for temperature measurement is in being able to either hold pressure constant and measure volume, or hold volume constant and measure pressure. Figure 2.2 shows a classical laboratory setup for implementing the latter type of measurement. A sealed bulb of the gas sample to be used for the temperature measurement is attached to a manometer (a pressure measuring instrument). The heart of this device is a column of fluid with a vacuum at the top. The height to which the column rises, is read off on an associated scale to indicate pressure. Unlike a typical manometer, this instrument also provides an auxiliary adjustment tube attached by a flexible coupling. The adjustment tube is moved up or down so that the level of the manometer's working fluid at the point which it interfaces with the gas bulb is maintained at a uniform level. This ensures that the gas sample in the bulb is maintained at a constant volume.

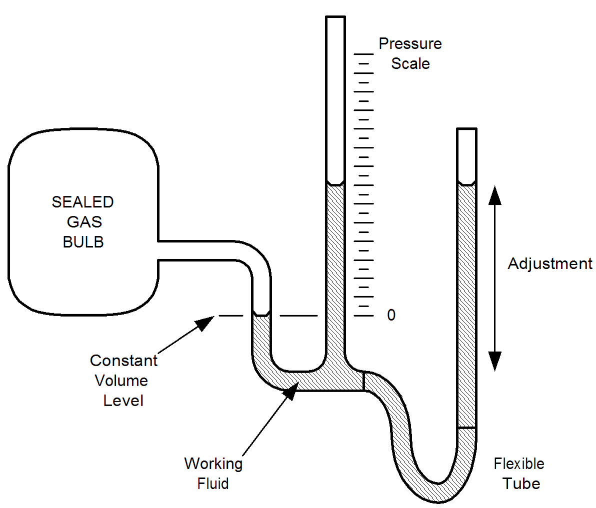

Figure 2.2 - Manometric Gas Bulb Thermometer

Although a manometric temperature sensor like the one shown above can provide significant advantages, its use is also subject to a number of limitations. For example, if a real gas is cooled to the point very close to absolute zero, its volume will not in actuality shrink to zero. At sufficiently low temperatures the gas will liquefy or even solidify, below which points it will contract much more slowly with decreasing temperature - as the material is no longer in its gaseous phase, it no longer obeys the ideal gas law. Also, under conditions where the 'gas' simultaneously exists in both gaseous and liquid phases, the ideal gas law no longer predicts pressure. Instead, pressure is determined by the material's vapor pressure, which is strictly a function of temperature.

If one operates a gas-law based thermometer under a suitable set of conditions, it can provide a high degree of linearity. This feature is especially important in being able to accurately measure temperatures which occur *between* key calibration points. For example, if one calibrates a thermometer at two points, for example the freezing and boiling points of water, one is only really assured of accurate measurements at those two points. If the thermometer is non-linear between those two points it can be difficult to establish an accurate temperature scale without thoroughly understanding the nature nonlinearity. If the effect being used as the basis for the temperature measurement is linear, as is the case for a gas thermometer, simple interpolation can be used to establish the scale between the two reference points. It is for this reason that gas thermometers were historically popular for making laboratory temperature measurements. It is also possible to replace the manometer arrangement of Figure 2.2 with an electronic pressure sensor for more flexibility, although this improvement requires one to take the non-linear behavior of the pressure sensor into account for calibration.

Ironically, one of the most common modern applications for gas thermometers is one that does not require laboratory-grade accuracy - thermostatic temperature control in appliances. In these applications, the pressure sensor or measurement device is replaced with a bellows which expands or contracts in response to the gas pressure. The bellows in turn activates either an electrical switch or opens and closes a valve. A major advantage of a gas temperature-sensor/valve arrangement is that it becomes possible to regulate the temperature of an oven or other heating device without the need for electrical power, resulting in a cost effective control system that can operate in environments where electricity may not be readily available.

2.3. Bimetallic Sensors

Solids, like liquids and gasses, also expand and contract in response to temperature changes. When temperature increases, most solids expand in all dimensions, as shown in Figure 2.3.

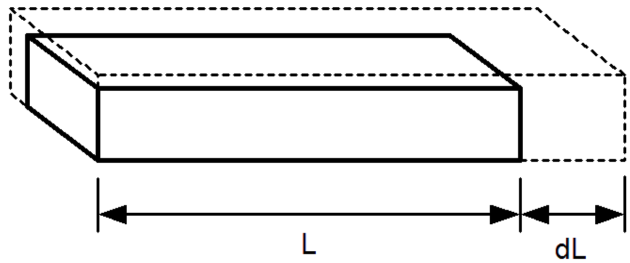

Figure 2.3 - Thermal Expansion of a Solid

For amorphous materials, such as glass and metals, the change in dimension is equal along all axis. For materials which have different properties along different axis, such as crystalline materials or materials with a grain structure such as wood, the degree of thermal expansion can differ significantly depending on the dimension along which it is measured.

Whereas the coefficient of thermal expansion for a liquid is normally characterized by changes in volume, the corresponding coefficient for a solid is normally characterized as change in length, or a linear coefficient of thermal expansion. The change in length of a solid (□L) for a small change in temperature (□T) can be described by

$$\Delta L = L_0 \cdot CTE \cdot \Delta T$$

where L_0 is the solid's initial volume. As is the case for CTEs of liquids, the CTEs of solids also vary based on the solid's composition and over temperature. Some linear CTEs for common materials are listed in Table 2. Note that even when one considers the geometric relationship between linear and volumetric characterization (□V□3□L), the CTEs for solids tend to be much lower than those for liquids.

Table 2.1 - Expansion Characteristics of Selected Solids

Material	**Linear Expansion (10^{-6}/□C)**
Brass	19
Steel	12
Glass	9
Diamond	1
Stainless Steel	17
Aluminum	23

While CTEs for solids are normally only a few tens of parts-per-million/C, they can manifest themselves quite noticeably. One familiar example can be seen when attempting to open a tight lid on a glass jar. By running hot tap water over the lid the resulting expansion of the lid is often enough to loosen it to the point where it can be easily removed.

If the thermal expansion effect in solids is so small, how can it be used to create useful sensors? The most common means of exploiting thermal expansion is through the bimetallic strip, where two strips of metals with differing CTEs are bonded together along their lengths, as shown in Figure 2.4

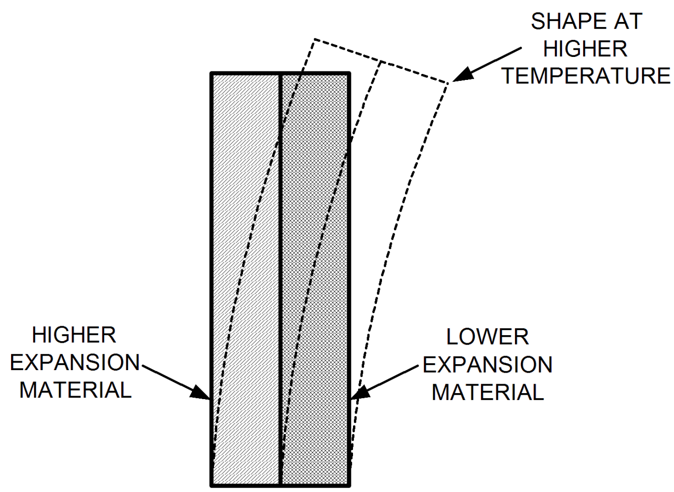

Figure 2.4 - Bimetal Strip

Because the two materials have differing CTEs, their lengths will change by differing amounts in response to temperature changes. While these changes in length may be small, and the difference between them smaller yet, these small differences will be reflected in a more noticeable change in the curvature of the bonded strip.

To implement a practical thermometer, the amount of curvature realizable with a short strip of material may not be sufficient. For this reason bimetallic strips are typically fashioned into a coil. One end of the coil is fixed, and an indicating pointer is affixed to the free end, as shown in Figure 2.5. This type of bimetallic thermometer is popular for many applications, one common example being the cooking thermometers used to determine whether meat is sufficiently ‘well-done‘.

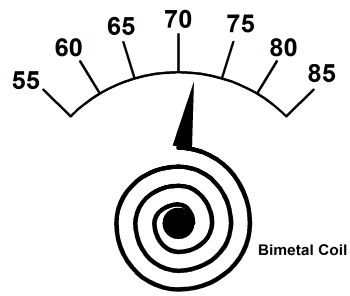

Figure 2.5 - Bimetal Thermometer

Another common application for bimetallic thermometers is in temperature controls. For example, if one replaces the indicator dial with electrical contacts, one can realize a temperature-sensitive switch.

Another way to exploit the bimetallic principal is to use a bimetallic disk rather than a strip. The disk is manufactured so that it has a slight convex bias to one side.

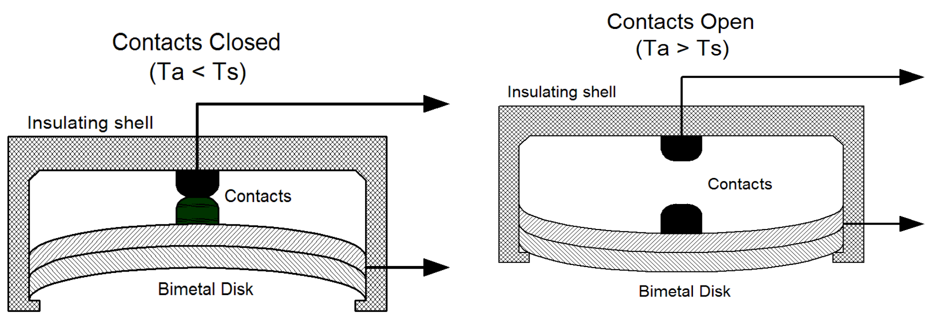

Figure 2.6 - Disk-type Thermostat

When the disk's temperature changes, the two metals expand or contract at different rates. At a certain temperature, the uneven expansion will cause the disk's convexity to snap from one side to the other. This motion occurs suddenly over a narrow range of temperature, unlike the case of the bimetallic strip, which deforms gradually. The 'snap-action' exhibited by the bimetallic disk is useful for several reasons. First, it provides a relatively large amount of mechanical displacement for opening and closing a set of electrical contacts. Secondly, the changeover in convexity from one state to the other occurs quickly, resulting in fast closing and opening of the contacts, which can reduce arcing and other contact wear effects. Finally, the snap action introduces hysteresis, a difference in the temperatures at which the device turns on and the at which the device turns off. Hysteresis is useful in many types of temperature control systems as it prevents heating and cooling equipment from being cycled on and off at an excessive rate. For all of these reasons, and their low cost, disk-type bimetallic thermostats are extremely popular temperature control devices in a wide range of applications.

2.4. Phase-Transition Temperature Measurement

Solids and liquids typically experience relatively small changes in length and volume as a result of temperature changes. Many materials, however, experience substantial changes in volume either during the transition between solid and liquid phases or close to the transition point. Water, for example, expands significantly just before it freezes into ice. Another example, familiar to anyone who has made candles or sealed canning jars with hot paraffin wax is that the wax shrinks substantially as it cools and solidifies from its molten state.

The dramatic changes in volume of waxes near their solid-liquid transition points is the basis of the wax-pellet thermostat (Figure 2.8). When the device is cold (Figure 2.8a), the wax pellet inside a canister is at minimum volume. This allows a pin to enter the canister to a maximal degree, resulting in the canister being forced into a valve-closed position by a return spring.

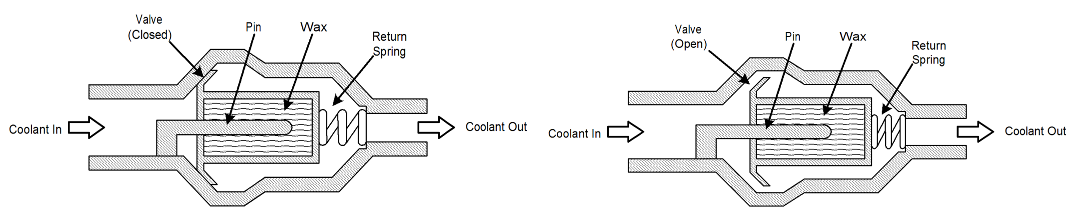

Figure 2.8 - Wax Pellet Thermostat in closed (a) and open (b) states

When the assembly heats up, the wax begins to melt and expand. This forces the pin out of the wax canister (Figure 2.8b), moving the canister against the return spring and opening the valve.

The trip-temperature of a wax thermostat is determined both by the device's mechanical design and by the temperature at which the wax experiences its greatest change in volume. This temperature, in turn, can be controlled to within a range of a few degrees to tens of degrees by careful formulation of the wax. Currently available thermostat waxes can provide volumetric changes in the range of 10%-20%, with transition temperatures ranging from approximately 20C to over 100C, depending on the formulation [ ].

Although wax thermostats can be used in a wide range of applications where one needs to obtain a mechanical motion in response to temperature changes over a relatively narrow range, perhaps the common application of wax pellet thermostats is in automotive cooling systems. When an engine is below its operating temperature, the thermostat remains in the closed position, preventing water from circulating through the radiator and being cooled. When the engine reaches operating temperature, the thermostat valve begins to open and allow water circulation, cooling the engine.

2.4. *Not* Sensing Temperature

Up to this point this chapter has focused on ways in which temperature may be detected through mechanical means. This section will present an example of the opposite goal - creating a system that is *insensitive* to the mechanical effects of temperature changes. Although systems such as these are not temperature sensors, they exploit the same basic principles, but used in different ways.

The pendulum clock was invented by Christian Huygens sometime around 1650, and was the first class of mechanical time-keeper that was consistently able to keep what would be considered 'good time' by modern standards. Previous timekeepers based on the flow of water ('water clocks') and mechanical escapements of other types were generally incapable of providing anywhere near the consistency of pendulum clocks. By the early 18th century, most high-quality clocks relied on the periodic oscillation of a swinging pendulum.

For an ideal pendulum with all of its mass concentrated into a 'bob' at its end, swinging through an arc of small angle, the time required to complete a cycle is given by

$$T = 2\pi\sqrt{\frac{l}{g}}$$

where l is the length of the pendulum (meters) and g is the earth's gravitational acceleration (~9.8m/s2). From this equation, one can see that the period of a pendulum is dependent upon its length. If the pendulum becomes longer, as it would through thermal expansion with increasing temperature, then the period also lengthens, slowing down the clock. Conversely, if the pendulum becomes shorter from decreased temperature, the period also shortens, and the clock will speed up. While the temperature of a clock may not be as much of a concern today when central heating and air conditioning are ubiquitous, neither of these amenities were available to the first owners of such clocks 300 years ago. Clocks intended for household or commercial use would have most certainly needed to be usefully accurate over a wide range of temperatures.

While thermal expansion effects in most materials is relatively small, as we have previously pointed out, time is a quantity that can be, and is, regularly measured to a surprising degree of accuracy. For example, if one were to use a pendulum constructed of brass (~18ppm/C), one could expect a clock's speed to vary by ±90ppm over a 10C temperature excursion. This corresponds to gaining or losing about 8 seconds per day, or roughly 4 minutes per month. Although annoying, this degree of inaccuracy might have been tolerable to many clock owners, especially if they were willing to periodically reset the clock. Certain application, however, such as marine navigation, demanded exceedingly consistent and accurate timekeepers.

There are many technological challenges involved in realizing a good clock mechanism, including precision fabrication of the components, reliable lubrication systems, and devising mechanisms that have low wear. After these and many other problems are solved, the ultimate factor limiting a pendulum clock's stability and accuracy is variation in the pendulum's length. One obvious solution to this problem would be to use a material with a low CTE, such as invar (~10^{-6}/°C). Unfortunately, highly engineered materials such as these would not have been available to early clockmakers, and more sophisticated solutions that could be realized with available materials would be needed.

One particularly elegant solution to the problem of maintaining a constant pendulum length in the face of varying temperature is the gridiron pendulum (Figure 2.9), invented by clockmaker John Harrison in the early 1700's. While this form is often seen in modern, electrically-regulated grandfather clocks, where its primary function is decorative, it is a key functional component in a mechanically-regulated pendulum clock.

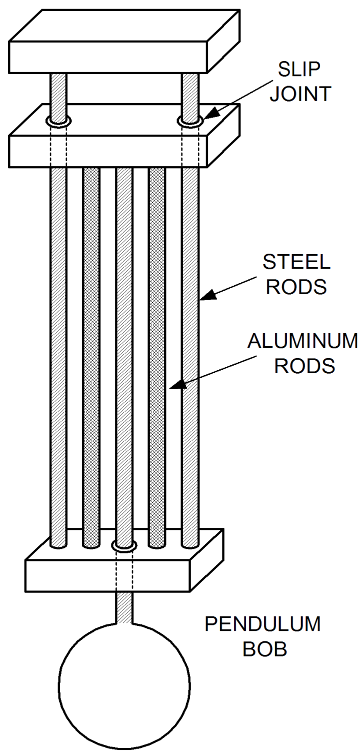

Figure 2.9 - Gridiron Pendulum

The gridiron pendulum exploits the differences in CTE between two different metals. In the example given in Fgure 2.9, the metals of interest are the steel and aluminum rods, with respective CTEs of $12x10^{-6}$/°C and $23x10^{-6}$/°C.

To understand how the gridiron works, assume that all of the rods are approximately the same length, and that all of the parts of the gridiron are at the same temperature. If the temperature increases by one degree, the steel rods on the outside lengthen by 12ppm (parts-per-million of their total length) and the lower block drops by that amount. The two aluminum rods, however, lengthen by

23ppm, raising the top block up by 11ppm (23ppm-11ppm). Finally, the steel rod connected to the bob lengthens by 12 ppm, but since it is fixed to the top block, which has just risen by 11ppm, the bob only descends by 1ppm. By exploiting the *difference* in expansion coefficients between the two materials (steel and aluminum), a gridiron pendulum exhibits a much lower overall coefficient of thermal expansion along its length.

Although we used aluminum in this example because its CTE is about twice that of steel and made for a simpler example and subsequent explanation, aluminum would not have been available to an 18th century clockmaker such as John Harrison. A more common option available at the time would have been brass, with a CTE of 18x10$^{-6/}$□C , which is about 1.5 times that of steel. This requires a somewhat more complex design to be able to achieve a temperature stable pendulum. We leave the implementation details as a problem for the reader. (hint - you need to use more rods than in the steel-aluminum case)

Further Reading/Bibliography

Thermometers:

"Liquid-in-Glass Thermometers", J.V. Nicholas, *The Measurement, Instrumentation and Sensors Handbook*, pp.32.117 - 32.128, ed. John G. Webster, CRC Press 1999.

Galinstan:

http://www.geratherm.com/docs/sicherheitsdatenblatt_galinstan_en.pdf

Wax Thermostats:

Wax-Pellet Thermostat, Yoshikazo Kuzi, U.S. Patent #4948043, August 14, 1990.

http://igiwax.com/industries-applications/thermostat-and-distillation-products.

Disk Thermostats:

Snap Disk Thermostat, D.J. Schmitt, U.S. Patent # 3451028, June 17, 1969.

John Harrison & Clockmaking:

Longitude, Dava Sobel, Walker & Co. New York, 1995.