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Mechanical (Hair) Hygrometer

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3 Mechanical (Hair) Hygrometer

3.1 HISTORY OF HAIR HYGROMETERS

According to historical sources (Pfaundler 1907; Brodgesell and Liptak 1993; Robens et al. 1994; Camuffo et al. 2014), the first mechanical hygrometers appeared in 1783: Swiss Horace Bénédict de Saussure invented the first hygrometer using a human hair to measure humidity (de Saussure 1783). A diagram illustrating the principle of the hair hygrometer operation is shown in Figure 3.1. Other variants of hair hygrometers are shown in Figure 3.2.

However, attempts to develop such hygrometers had been undertaken before. For example, in 1626, for medical purposes, Sanctorius (1626) invented hygrometers based on the change in length of a ballasted cord (Figure 3.3). A cord was stretched horizontally on a wall, and from its center, a ballast ball was suspended. When the relative humidity increased, the cord was tightened and the ball was lifted. This model is very similar to the string hygrometer developed by Folli and Viviani (Figure 3.4). This model was developed around 1664 (D’Alancé 1707).

The hair hygrometer designed by de Saussure is based on a sorption method. It uses the characteristic of the hair so that its length expands or shrinks the response to the relative humidity (Sonntag 1994). The hair shrinks when humidity drops and swells when humidity increases; similarly, cordage and catgut are shortened and untwisted by moisture. For example, the length of a human hair from which liquid is removed increases by 2.0%–2.5% when relative humidity changes from 0% to 100%. A humidity change takes an effect on the moisture content in such materials. The hair is made from keratin,
a protein that is wound into a coil. The turns of the coil are held together by hydrogen bonds. These bonds break in the presence of water, allowing the coil to stretch and the hair to lengthen. The bonds reform when the hair dries, which allows people to style their hair simply by wetting it, shaping it, then drying it. Different types of human hair show different changes in length. However, there is still a relationship between the length of hair and relative humidity. Therefore, manufacturers generally use a bundle of hairs. This averages the individual responses of each strand, since different hairs respond at slightly different rates of expansion and contraction. One should note that the dimensions of various organic materials also vary with their moisture content.

Variants of more advanced hair hygrometers are shown in Figure 3.5. The hair is hygroscopic (tending toward retaining moisture); therefore, in the late 1700s, such devices were called hygroscopes by some scientists. That word is no longer in current use, but hygroscopic and hygroscopy, which derive from it, still are. The traditional folk art device known as a weather house works on this principle. The length change in hair hygrometers may be magnified by a mechanism (see, for example, Figure 3.6).

FIGURE 3.3 Sanctorius hygrometer based on the change in length of a cord ballasted in the middle. (Reprinted from www.imss.fi.it.)

FIGURE 3.4 String hygrometer by Folli and Viviani with rotating pointer. This model is presented in Museo Galileo-Institute and Museum of History of Science, Florence. (Reprinted from http://imss.fi.it.)

FIGURE 3.5 (a, b) Variants of the hair hygrometer designed by Horace Bénédict de Saussure (1783): (a) Hand hygrometer; (b) Large hygrometer; (c) Museum exhibit, hand hygrometer: 1, zero adjustment; 2, hair; 3, nonlinear graduation in relative humidity; 4, roller with pointer; 5, prestressing weight. (a, b - reprinted from Saussure 1783/1900, www.galltec-mela.de/histoire; c - reprinted from http://americanhistory.si.edu.)
3.2 FEATURES OF HUMIDITY CONTROL USING HAIR HYGROMETERS

The hair hygrograph or hygrometer is considered to be a satisfactory instrument for use in situations or during periods in which extreme and very low humidity are seldom or never found. The hair hygrometer is not expensive, and its usage is simple. Some types record on a chart driven by clockwork or batteries. Very basic types are not powered at all. Electronic sensor-based hygrometers are usually preferred now, but many mechanical hygrometers remain in use for room monitoring (see Figure 3.7a, b). However, the response of the hair to humidity is nonlinear. In addition, the response tends to drift over time, and this response is characterized by hysteresis: The hair length changes more when the humidity increases than when it decreases. The change of the hair length observed when the humidity increases is up to 5%–6% larger than that observed when the humidity decreases. The response time of the hair hygrometer also depends on the air temperature. The time constant of the hair hygrometer is approximately 10 seconds at 20°C and approximately 30 seconds at −30°C. The hair is also highly sensitive to contamination, such as dust, ammonia, oil, and exhaust gas.

It was established that, by rolling the hairs to produce an elliptical cross-section and by dissolving out the fatty substances with alcohol, the ratio of the surface area to the enclosed volume increases and yields a decreased lag coefficient, which is particularly relevant for use at low air temperatures. This procedure also results in a more linear response function, although the tensile strength is reduced. For accurate measurements, a single hair element is preferred, but a bundle of hairs is commonly used to provide a degree of ruggedness. Chemical treatment with barium (BaS) or sodium (Na₂S) sulfide yields further linearity of response.

Testing has shown that 20%–90% relative humidity (RH) is the best range for hair hygrometer usage. The accuracy attainable by hygroscopic techniques in this range of humidity is typically within 5%–10% relative humidity, but like many other instruments, hair hygrometers can be more accurate in the middle of the relative humidity scale than at the very high or low ranges. Accuracy may be closer to ±2–3% RH between 40% and 60% RH at room temperatures. Outside of that range, accuracy will decline. Accuracy depends on many factors. Sources of measurement error include the response of different hairs and the response of the mechanical linkage that connects the hair to the indicating scale. Accuracy depends also on the conditions of exploitation. For example, after the hair hygrometer is exposed in low temperature and low humidity for a long time, reading error increases due to the increasing of delay. If a hair hygrometer is left in a low-humidity condition for a long time, its reading changes cause large errors as well. To improve accuracy, the device should be calibrated in the room where it will be used, and calibrated at a condition in the humidity range expected for the room. Thus, users should maintain a healthy skepticism concerning a hair hygrometer’s readings, including those devices that are marketed as “certified.” Often, a small tap with a finger is enough to change a humidity reading by 3%, as the mechanical linkage can seize up over time. They are best used as a general indication of humidity rather than for important readings.

Hair hygrometers, similar to the wet and dry bulb hygrometers discussed in Chapter 4, require good circulation of the measured gas. In air ducts, there is generally an adequate gas velocity to ensure a
dependable measurement; however, if the instrument is to be mounted in a room, the location must be carefully chosen. The instrument should not be mounted near the doors or other openings where it will be exposed to spurious drafts; flush mounting on a panel should be avoided, because the atmosphere in the back of the panel is stagnant. The hair element can be mounted on the top or back of the instrument case, depending on the installation. The element can also be mounted on an extension in the back of the instrument so that the sensing portion is in the room or compartment where relative humidity is to be measured, while the readout device is surface mounted on the wall outside (Brodgesell and Liptak 1993).

### 3.3 OTHER TYPES OF MECHANICAL HYGROMETERS

Besides hair in the earlier versions of mechanical hygrometers, some other materials have been used. Paper, for example, also changes length at air humidity change (see Figure 3.8). However, unlike hair, paper does not have the necessary reproducibility and stability parameters. In addition, its properties are strongly dependent on the manufacturer and composition.

There have also been attempts to develop wood-based hygrometers using volumetric changes of the material. As is known, wood shrinks at low RH and swells at increasing levels. Following this principle, a hygrometer was developed to monitor such dimensional changes and transform them into a rotation of a pointer on a circular scale (Figure 3.9).

In museums, one can also find hygrometers, using humidity-sensitive materials such as leather, horn, and ivory (Camuffo et al. 2014). One was developed in 1687 by Guillaume Amontons. A hygrometer was composed of a vertical glass tube, 3 feet long, and at the bottom, a leather bag filled of mercury was applied. When air was moist, the leather bag expanded and mercury descended in the tube (Amontons 1695; Berryat 1754). The bag with the mercury moved the interface level of two immiscible liquids up and down in the tube.

It should be noted that the mechanical hygrometers can be designed based on principles different from those shown in Figures 3.1 through 3.9. For example, a laminate hygrometer or the metal–paper coil hygrometer shown in Figure 3.10 is made by attaching thin strips of wood or paper to thin metal strips, forming a laminate. The laminate is formed into a spiral or a helix. As the humidity changes, the spiral flexes, due to the change in the length of the wood or paper. One end of the spiral is anchored, and the other is attached to a pointer (similar

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**FIGURE 3.8** Hygrometer of the type invented or perfected by Vincenzo Viviani (second half seventeenth century). The hygroscopic substance is a paper ribbon. The brass bar has a small, turned column at each end. The columns carry two small rolls, on which the ends of the paper ribbon are wrapped. The ribbon is weighted at the center by a wooden staff carrying a small pointer (the ribbon and staff are modern restorations). The changes in atmospheric humidity cause variations in the length of the paper ribbon, which are registered on a scale. (Reprinted from www.imss.fi.it.)

**FIGURE 3.9** Volumetric hygrometer based on wood shrinkage and swelling. (Reprinted from www.imss.fi.it.)

**FIGURE 3.10** Hygrometer using metal/wood or metal/paper laminate. (Reprinted from https://learn.weatherstem.com.)
Mechanical (Hair) Hygrometer

to a bimetallic strip used in temperature measurements), and the scale is graduated in percentage of humidity. Such a configuration is useful for giving a dial indication of humidity changes. Hygrometers, which use indicated approach, appear most often in very inexpensive devices, and their accuracy is limited, with variations of 10% or more.

A contemporary adaptation of the hair hygrometer is the plastic expansion hygrometer. In this popular and economical instrument, the hair is replaced by a hygroscopic polymer, such as nylon, polyimide plastic, or cellulose. Like human hair, synthetic polymer materials change length as the water vapor concentration varies. This elongation has been used to build dial and digital indicators and also relatively inexpensive industrial thermostats, humidistats, and residential furnace humidifiers. The operation of polymer-based element instruments is similar to the previously described human hair hygrometers. While the hygroscopic polymer is more uniform than human hair, the same advisory cautions apply—do not expect accuracy greater than ±7% RH, calibrate them regularly in the environment where they are used, and do not expect accuracy if wide swings in RH are common. In addition, because of the long lag time for synthetic fibers, such sensors should never be used below 10°C.

3.4 HYGROGRAPHS AND HYGROTHERMOGRAPHS

In addition to devices that provide information on air humidity, there is a large group of instruments, hygrographs, recording these changes in time (see Figure 3.11). This is the most commonly used hair hygrometer. This uses a bundle of hairs held under slight tension by a small spring and connected to a pen arm in such a way as to magnify a change in the length of the bundle. A pen at the end of the pen arm is in contact with a paper chart that has been fitted around a metal cylinder and registers the angular displacement of the arm. The cylinder rotates about its axis at a constant rate determined by a mechanical clock movement (see Figure 3.12). The rate of rotation is usually one revolution per week or per day. The chart has a scaled time axis that extends around the circumference of the cylinder and a scaled humidity axis parallel to the axis of the cylinder. The cylinder normally stands vertically. The mechanism connecting the pen arm to the hair bundle may incorporate specially designed cams that translate the nonlinear extension of the hair in response to humidity changes into a linear angular displacement of the arm.

Modern humidity recorders based on a mechanical hygrometer are generally available as two-pen instruments, with the second pen recording temperature (see Figure 3.13). Such hygrothermographs have been the basic monitoring tool in museums for some time. They provide a continuous record of the temperature and humidity variations over a period of 1, 7, 31, or 62 days. Hygrothermographs are accurate within ±3% to 5% when properly calibrated. They are the most accurate within the range of 30%–60% RH. Transmitters are available in both digital and analog designs, and the analog ones can be electronic or pneumatic (Brodgesell and Liptak 1993).

FIGURE 3.11 Old retro hygrograph with the function of recording the change in humidity over time. (Reprinted from www.shutterstock.com.)

FIGURE 3.12 Hair hygrograph. Diagram illustrating the mechanism of recording the change in humidity over time. (Reprinted from www.daviddarling.info.)
3.5 ELECTRONIC EXPANSION HYGROMETER

In the mechanical hygrometer, the change in expansion of material is measured and indicated by a mechanical linkage of gears, levers, and dials. A modification of this concept replaces the linkage with electronics. The hair, plastic, and, in one case, a desert plant seed case are connected to an electronic strain gauge that measures the pressure exerted as the sensing element contracts. This is often an improvement over mechanical hygrometers, since electronics tend to be more repeatable than linkages, particularly over long periods of time.

Another approach was realized by Ha et al. (2000). They proposed so-called mechanical-optoelectronic humidity sensors (see Figure 3.14). This device consists of a light emitting diode (LED), a very sensitive photodiode, and a mechanical system. The sensor has a bunch of human hair at one end, and the other end has a thin metal sheet with a fittable window with respect to the LED and photodiode. A spiral spring is connected with the metal sheet. When the humidity concentration changes, the contraction and expansion occur in the hair; this hair pulls the metal sheet up or down. Thus, the window opening area changes and varies the light intensity to the photo detector from the LED, resulting in a photocurrent change with respect to humidity on the output side. Developers argue that this sensor has good linearity, long life, small hysteresis, stable operation, and less temperature dependency.

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