HUMIDITY SENSORS AND MEASUREMENT

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Your local weather forecast probably includes relative humidity and dew point. Beyond that, most of us don't think much about humidity or how it is measured. Actually, though, measuring and controlling humidity touches many areas of our lives beginning with interior comfort – heating, air conditioning, humidifiers and dehumidifiers. This extends to building and warehouse control and to transportation of moisture-sensitive goods.

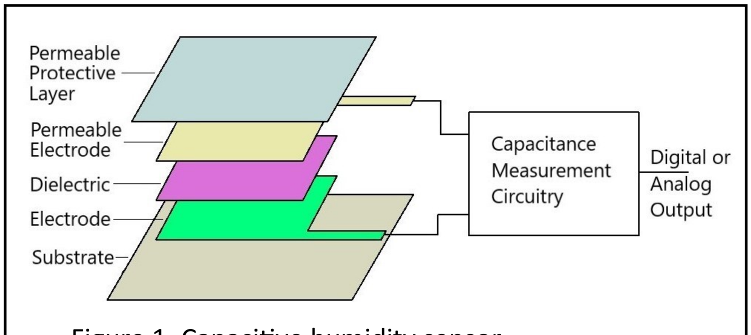

Figure 1. Capacitive humidity sensor.

Medical applications include incubators, nebulizers and CPAP machines plus, of course, the atmosphere inside hospitals. Many manufacturing processes are humidity sensitive including most foods, ceramics and paper manufacturing. Tobacco processing has been mentioned as particularly sensitive. Gas pipelines must measure and minimize the water vapor in them. Electronic assembly areas should be humid enough to avoid static electricity but not excessively humid.

There are many ways to measure humidity or water vapor. Some applications require precise equipment or complex systems plus training and periodic maintenance. Others, especially ambient monitoring, need only inexpensive, readily available, easy to use sensors. This paper focuses on them.

Most electronic humidity sensors today use capacitance change to measure humidity. Several manufacturers offer relative humidity (RH) sensors, complete with digital or analog outputs, for just a few US dollars. Accuracies typically are around 2% to 4% RH. We'll focus on them first, then look at the relationship between dew point and relative humidity. We'll finish with a brief review of other measurement technologies.

Capacitive Sensor Technology

A capacitor is simply two electrodes with a dielectric (insulating) material between. If the dielectric is moisture sensitive it can be used to measure humidity.

Figure 1 shows the concept. A lower electrode is deposited on a substrate, usually silicon, sometimes glass. A thin humidity-sensitive dielectric layer comes next. This usually is polymer, sometimes porous metal oxide. A top electrode, water permeable, is added, then the sensor is covered with a permeable protective layer to protect it from contamination and liquid water droplets or condensation. Most actual sensors use integrated circuit manufacturing methods. Electronic circuitry converts the capacitance measurement to a digital or analog output.

The water molecule is highly polarized. Water has a dielectric constant of about 80, as opposed to maybe 2 to 15 for typical polymers. If the dielectric is hygroscopic – able to absorb moisture – its dielectric constant or permittivity will increase as humidity goes up, increasing the capacitance. When the humidity drops the dielectric will give up some of its absorbed water and the capacitance will go back down.

The polymer's capacitance varies *almost* (not exactly) linearly with relative humidity, easing the circuit design. Also, it is not much affected by temperature changes and has good long-term stability. The capacitance is small, though, and changes only modestly with humidity. A typical sensor quotes 180 picofarads nominal, changing about 17% (31 pf) from 0 to 100% RH. The measurement circuit's capacitance, and even just a few inches of connecting wire or cable, can cause significant error.

Most sensors combine complete measurement circuitry with the sensor in a single integrated circuit (IC). This of course eases system design. Connection capacitance problems are eliminated and the measurement circuit's capacitance is taken into account in the manufacturer's design and specifications. Most such ICs also include a temperature sensor.

Typical Capacitive Sensor Products

Stand-alone sensors. Sensors with no electronics seem to be becoming obsolete. I found only a few, and some were labeled "obsolete". All but one required user calibration in a humidity chamber for accuracy. Even that one would become inaccurate unless design precautions were taken to minimize connection and circuit capacitances. Typical values were 180 or 330 pf, with capacitance changes around 17% for a humidity change from 0 to 100% RH. All were larger than typical IC sensors, in enclosures with two pins for thru-hole circuit board mounting.

Digital output sensors. Integrated sensors with digital outputs have become common, offered by several manufacturers for just a few dollars. Most, probably all, include temperature sensors. Figure 2 outlines the basic structure.

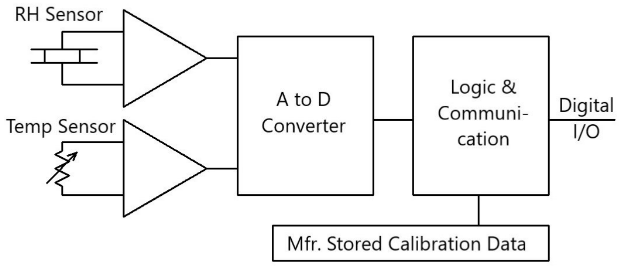

Figure 2. Integrated humidity sensor.

±2% RH midrange accuracy at room temperature is common, loosening to 3% or 4% for humidities near 0% or 100% RH. Some have looser accuracy specs, between 3 and 5%. Because they are digital they can easily be calibrated by the manufacturer. They also can correct the linearity deviations of the sensor and at least partially compensate for temperature changes.

Some operate between -25 and +85 deg. C while others go higher, -40 to +100 or +125^{O}C. The output usually is I^{2}C (Inter-Integrated Circuit) serial communication, carrying both RH and temperature data. This usually is compatible with the SPI (Serial Peripheral Interface) bus.

Analog output sensors. Analog output sensors include capacitance-to-DC conversion circuitry. Most have *ratiometric* voltage outputs, meaning the output is proportional to the supply voltage. For example, a 50% output will be 2.5 volts with a 5V supply, 2.0 volts at 4V supply and 1.65 volts with a 3.3V supply. Those with temperature sensors have separate analog outputs for humidity and temperature.

While researching this article I found only four manufacturers who offer analog outputs. Two, Honeywell and TDK, are strictly analog, capacitance only, no temperature measurement, per Figure 1 with analog output. They are "nearly" linear but cannot correct for linearity deviations or temperature effects. Linearity deviations are about ±2%. Temperature decreases the output by about 0.22% per deg. C. At 25^{O}C and mid-range humidity, accuracy specs are in the ±3% to ±5% RH ballpark

The other two, Sensirion and TE, include temperature sensors and actually are digital inside. Their operation is the same as the digital block diagram of Figure 2 but with digital-to-analog (D/A) conversion added for the analog outputs. Being digital, they include linearity and temperature correction and manufacturer calibration. Their accuracy specs are about the same as digital sensors. Two analog outputs are provided, one each for RH and temperature.

Honeywell, Sensirion and TE also sell digital output sensors. TDK apparently does not.

Typical Specifications – Capacitive IC Sensors.

As mentioned earlier, most IC sensors have 2%, 3% or 5% mid-range accuracy at room temperature, loosening another percent or so below 10% and above 80 or 90% RH. Most are specified over at least -25 to +85^{O}C: many cover -40 to +100 or

+125^{O}C. The several manufacturers have various offerings with a range of accuracies, specs and costs. This summary does not include stand-alone sensors with no electronics.

Temperature range & temperature compensation – often not clear. If you are operating over an extended temperature range you'll need to study the spec sheets carefully and maybe contact the manufacturer. Some are not very clear about accuracy versus temperature. Others are but, even if compensated, show accuracy charts only over a narrower range such as 0 to 70^{O}C. Some that are compensated list a 0.15% RH/^{O}C (maximum) temperature coefficient. After reviewing many spec sheets, it seems that best accuracies are between 10 and 80 or 90% RH and between -20 and about +60^{O}C.

Uncompensated sensors are primarily influenced by the fact that the dielectric constant of water vapor itself changes with temperature. At 0^{O}C it is about 8% higher than at 25^{O}C. At 100^{O}C it is about 30% lower.

Hysteresis (the difference between upscale and downscale readings): Typically $\underline{+}$1% RH or better.

Response time: Typically 5 seconds for 63% response in still air. May be much slower if the sensor is inside an enclosure. Note, though, that the sensor may need much longer to recover after an extended time at high humidity.

Protective covers. Many manufacturers offer an *optional* hydrophobic, water-repellant coating. This protects the sensor from wet dew droplets, dust, salts and other contamination.

Gases, chemicals. Some gases and chemicals have little or no effect. Natural gas and propane are two examples. Others may upset accuracy or damage the sensor. Consult the manufacturer or run your own tests for "dirty" applications.

Where to find them.

Start with your favorite electronics distributor's web site such as Digikey (digikey.com) or Mouser (mouser.com). One gave a choice between board mount or industrial sensors. You'll want board mount: industrial sensors are complete instruments or assembled industrial probes. You then should be able to use their selection charts to narrow your choices – digital, analog, mounting style etc. It may take a while – there are a lot of choices, especially for digital!

Some of the major manufacturers are Amphenol Advanced Sensors (Telaire), Honeywell, Sensirion, Silicon Labs, TE Sensors (Measurement Specialties) and Texas Instruments. On a recent design project for an industrial application our client selected a digital I^{2}C sensor from Sensirion.

If you're an experimenter, SparkFun electronics (sparkfun.com) has 'breakout boards' #Si7021 & SHTC3 ready to go for I^{2}C communication. Arduino (arduino.cc) and Jameco (jameco.com) have a few offerings. Radio Shack has a humidity/temperature sensor for Arduino, #OSEPP (out of stock as I am writing this). There probably are others.

Dew Point vs Relative Humidity.

Relative humidity measures how much moisture the air has versus how much it can hold. Air can hold more water vapor when it is warm, so warm air at 50% RH has more moisture than cool air at 50%. As warm air cools it can hold less water, so its *relative* humidity will go up. The *absolute* humidity, the actual amount of moisture in the air, will not. If the relative humidity reaches 100% and continues to cool, the excess moisture will condense, forming dew. The temperature where that happens is called the *dew point*.

Dew point is a measure of absolute humidity. On a warm summer night in Florida the dew point might be 70^{O}F (21.1^{O}C) or higher with close to 100% RH. Next afternoon, as the temperature reaches 90^{O}F (32.2^{O}C) the dew point still will be 70 degrees but the relative humidity will be only 52%. By the way, this assumes normal atmospheric pressure. The temperature seldom goes below the dew point, because condensing water releases a lot of stored energy.

How do we calculate one if we know the other (plus temperature)? Easy – go to your favorite search engine and type "calculate dew point" (or humidity)!

More seriously, the computation is not straightforward. The equations are complex and involve exponentials or logarithms. Most are close approximations but not absolutely correct. Quite commonly, dew point is computed in a microprocessor using the RH and temperature values from a digital humidity sensor. One of the better known equations is called the *Magnus Formula*. You can find it in a search: we'll not reproduce it here. I found it in the Wikipedia article on dew point.

Here's a simple approximation said to be *fairly* accurate, to about $\underline{+}1^{O}$C dew point, for humidities *above 50%*:

Dew Point = Temperature - (100 - RH)/5.

Dew point and temperature are in Celsius. A measurement accuracy of $\underline{+}3\%$ RH translates to $\underline{+}0.6^{O}$C (1.1^{O}F) dew point.

Figure 3 shows a humidity chart from Wikipedia's Dew Point article, per Creative Commons license.

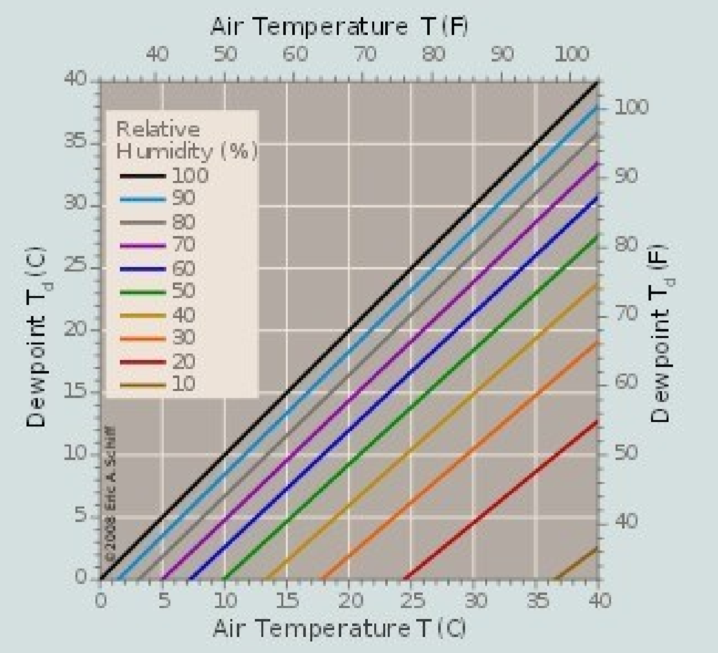

Figure 3. Humidity/dew point chart. (Credit - Wikipedia - Dew Point article.)

Dew Point – Chilled Mirror Measurement.

Simple to describe, simple to diagram (Figure 4), not so simple to design and use. The basics – you cool a mirrored surface while measuring its temperature. When dew forms, that's the dew point. An LED light reflected off the surface detects dew formation. In an automated system the temperature is controlled to the point where dew just forms.

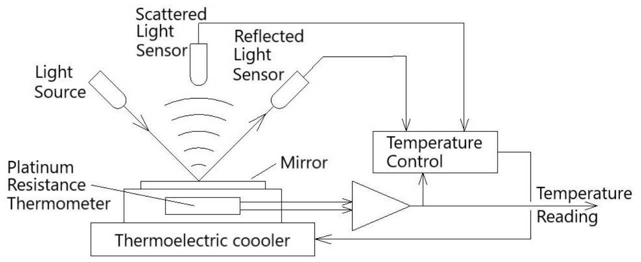

Figure 4. Chilled mirror dew point measurement.

Without dew the beam reflects cleanly and is picked up by the reflected light sensor. When dew forms the surface become cloudy, diffusing the beam. The direct sensor receives less light, the scattered light sensor receives more. (Not all system diagrams include a scattered light sensor.) Control electronics works to maintain the temperature at the point where dew just begins to form. There are other designs, including hand-operated systems where the user looks for dew.

This is a basic, fundamental measurement and can be very accurate. The technology allows designs capable of reading far below freezing (frost point): one paper mentioned minus 95^{O}C. It's very expensive, however, and requires training for operation and maintenance. A high level of maintenance is needed. It is slow.

Chilled mirror is best used for high-accuracy laboratory use and as a reference standard when calibrating other sensors. Its environment must be clean. Dust, pollution and contaminants on the surface obviously will affect operation. Salt, for example, will condense water above the dew point. Some coatings might delay condensation or interfere with reflection. The mirror must be inspected and cleaned periodically. The concept is not well suited for most process measurements. According to a Wikipedia article on Automated Airport Weather Stations, the National Weather Service changed from chilled mirror to a custom-modified Vaisala capacitive sensor due to problems with the chilled mirror sensor.

Here's an idea from a home experimenter's article. Take a can with a shiny surface. Fill it partway with water and put a thermometer in. Add some ice cubes, stir, add more ice, stir, etc. When you see condensation on the can, read the thermometer. That will be the dew point!

Other Measurement Technologies – a brief review.

Virtually all the readily-available humidity sensor components today are the capacitive polymer type. Here's a brief review of other technologies.

Aluminum oxide capacitive sensors. These are similar to polymer capacitive sensors but the dielectric is porous anodized aluminum oxide, not polymer. The porous aluminum oxide (alumina) absorbs water vapor, increasing its capacitance. This technology usually is sold as complete industrial monitoring systems and probes, not components. It is said to measure down to very dry atmospheres – dew points down to -90 or -100^{O}C. One important application is measuring the moisture in natural gas or propane pipelines. This obviously requires a rugged and well-designed monitoring system.

Advantages include mechanical strength, thermal stability and resistance to chemical attacks. Measurement of very low dew points is another. They are not as linear as polymer sensors, though, and apparently have more hysteresis and are more affected by temperature changes. Aluminum oxide systems mostly are made to measure dew point, not relative humidity.

It's hard to know the basic sensor's performance because most published specifications are for complete instruments or systems. Our search did not find any off-the-shelf IC-like alumina components, although possibly they exist. We did, though, find a paper from 2010 describing experimental work toward that idea.

Resistive humidity sensors. These sensors measure resistance or electrical conductivity of a water-sensitive nonmetallic conductive material. The material is deposited as a film on top of a pair of electrodes – see Figure 5 – then covered with a humidity-permeable protective layer. As it absorbs water its conductivity increases (resistance decreases). The sensing layer may be salt, conductive polymers or other materials. In my search I found only one sensor based on resistance, from Thermometrics/ Amphenol Advanced Sensors. It had no electronics – only the sensor – and appeared to be an older product. There may be others, but I did not find them.

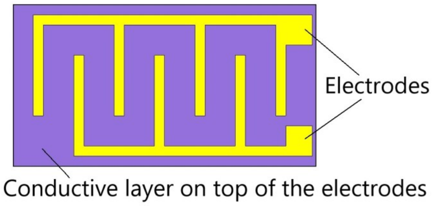

Figure 5. Resistive sensing element.

Their chief advantage is, the measurement is not affected by connection capacitance or normal cable resistances. The Thermometrics sensor is 55kohms at 50% RH and 25^{O}C.

Other than that, they have many disadvantages. Resistance versus RH is very nonlinear, decreasing as humidity rises, and is highly affected by ambient temperature. Unless you can find one with built-in electronics, circuit design may be a problem. Condensation and water droplets must be avoided and they are much more sensitive to chemical vapors and other contaminants. The one I found showed response time in the minutes, not seconds. It also warned against using direct current for measurement.

Thermal conductivity – absolute humidity sensors. This is not something you will find as an off-the-shelf component.

The thermal conductivity of air varies with humidity. Two identical sensors are used. One is exposed to air, the other is sealed in a small chamber with dry air or, more likely, nitrogen. The exposed sensor, of course, must be shielded from air flow or breezes.

If the air were perfectly dry, both sensors would read the same. With humidity, they will differ. According to one article the difference is directly proportional to absolute, not relative, humidity. Absolute humidity is related to dew point but is not the same. This method is good for high temperatures and corrosive environments.

Infrared. Water molecules absorb certain infrared wavelengths and not others. Early in my career I was involved in a project developing an industrial instrument to measure the amount of water in paper being produced on a paper mill. It used a rotating wheel with three different infrared filters. We also experimented with it for food manufacturing processes such as breakfast cereal.

Today we have lasers and tunable LED sources to do a much more precise job. Various designs are used to monitor the water content of air and gases.

Oscillating quartz crystals. A quartz crystal coated with a hygroscopic (water absorbing) material increases its mass with humidity. This changes its resonant frequency and can be used to measure humidity.

Lithium chloride dew point sensor. I think this is obsolete so I'll not go into much technical detail. In the 1980s the company where I worked (YSI, Inc., Yellow Springs, OH) made these. I designed the electronics for an industrial version and still have some literature. Figure 6 shows the design. YSI has not made it for years and I could not find any mention of this technology in a web search.

The basic idea - a wick was wound around a temperature sensor and impregnated with lithium chloride salt. Lithium chloride absorbs water readily – much more so than table salt (sodium chloride). Two electrode wires were wound around the wick and a controlled AC voltage applied. As the sensor absorbed water, current flowed, warming the sensor. The temperature rose until equilibrium was reached – the water evaporating at the same rate it was absorbed. The temperature was *approximately* proportional to the dew point.

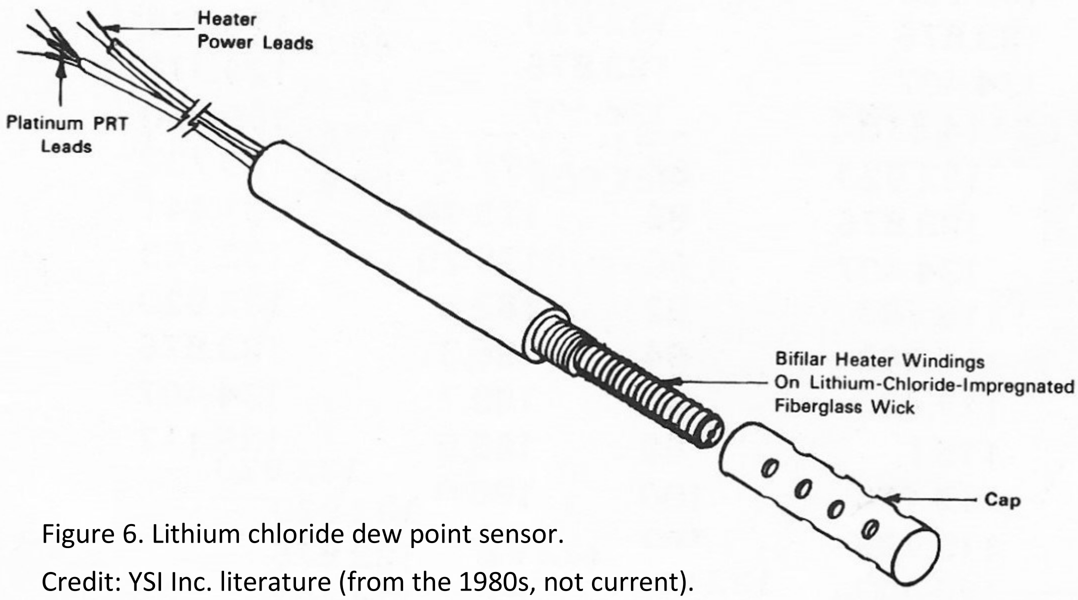

Figure 6. Lithium chloride dew point sensor.

Credit: YSI Inc. literature (from the 1980s, not current).

This sensor required some care. If unpowered it would absorb enough water to drip, losing its salt and becoming inaccurate or inoperable. Power outages could cause problems: so could water droplets or spray. When not in use it had to be stored in an airtight container. Contaminants could prevent proper operation - the wick would need to be cleaned, dried and resoaked in a solution with the correct percentage of lithium chloride.

Non-Electronic Humidity Measurement.

Human hair. Human hair, wool and some other materials, under tension, lengthen with humidity. Humidity gauges have been made using this principle. Mechanical linkages amplify the motion to move a pointer.

Paper/metal coil. Similar to a bimetal thermometer, a paper strip impregnated with salt is attached to a coiled metal strip. The coil moves an attached pointer as the paper expands or contracts with humidity. This often is used in nonelectronic home humidity gauges. Accuracy is limited – maybe 10 percent RH.

Wet/dry bulb. You've probably seen these – two thermometers side-by-side, one dry, the other having its bulb covered with a wet sock. Evaporation cools the wet bulb and you use a chart to convert the wet and dry temperatures to relative humidity. Evaporation rate is affected by air flow so for better accuracy a *sling psychrometer* lets you whirl the two around in the air before taking a measurement.

Conclusion.

When planning this paper the main intent was to review and cover component-level humidity sensors. Somewhat to our surprise we found that virtually all of them are based on polymer capacitance technology, most with built-in digital or analog signal processing. They are readily available at modest cost from a number of manufacturers. Accuracies in normal ambient conditions are around 2% to 4% RH.

We spent some time reviewing dew point versus relative humidity, then discussed chilled mirror dew point measurement. This is a basic measurement, capable of very good accuracy, but is not simple to design and use. It serves well in the laboratory and as a reference standard for calibrating other sensors.

We finished with a quick review of a few other measurement technologies, finishing with some non-electronic methods that still are in use today.