HUMIDITY SENSOR THEORY AND BEHAVIOR

SENSOR CONSTRUCTION: Relative humidity sensors use an industrially proven thermoset polymer, three layer capacitance construction, platinum electrodes and except for high temperature versions (shown bottom), on-chip silicon integrated voltage output signal conditioning. (RHIC Sensor).

In operation, water vapor in the active capacitor's dielectric layer equilibrates with the surrounding gas. The porous platinum layer shields the dielectric response from external influences while the protective polymer over layer provides mechanical protection for the platinum layer from contaminants such as dirt, dust and oils. A heavy contaminant layer of dirt will slow down the sensor's response time because it will take longer for water vapor to equilibrate in the sensor.



TEMPERATURE & HUMIDITY EFFECTS: The output of all absorption based humidity sensors (capacitive, bulk resistive, conductive film, etc.) are affected by both temperature and %RH. Because of this, temperature compensation is used in applications which call for either higher accuracy or wider operating temperature ranges.

When temperature compensating a humidity sensor, it is best to make the temperature measurement as close as possible to the humidity sensor's active area, i.e. within the same moisture micro-environment. This is especially true when combining RH and temperature as a method for measuring dew point.

Industrial grade Humidity and Dew Point instruments incorporate a 1000 ohm Platinum RTD on the back of the ceramic sensor substrate for unmatched temperature compensation measurement integrity. No on-chip signal conditioning is provided in these high temperature sensors.



VOLTAGE OUTPUT: The RHIC sensor linear voltage output is a function of V_{supply} , % RH and temperature. The output is "ratiometric," i.e. as the supply voltage rises, the output voltage rises in the same proportion. A surface plot of the sensor behavior for temperatures between 0°C and 85°C is shown in the graph below. This surface plot is well approximated by a combination of two equations:

 A "Best Fit Line at 25°C," or a similar, sensor specific equation at 25°C. The sensor independent "typical" Best Fit Line at 25°C (bold line in graph) is:

 $V_{out} = V_{supply} (0.0062 (\% RH) + 0.16)$

A sensor specific equation can be obtained from an RH sensor printout. The printout equation assumes $V_{supply} = 5$ VDC and is included or available as an option on every sensor.

2. A sensor independent equation which corrects the %RH reading (from the Best Fit Line Equation) for temperature, T:





The equations above match the typical surface plot (Best Fit Line at 25° C) or the actual surface plot (sensor specific equation at 25° C) to within the following tolerances:

±1%	for	T>20°C
±2%	for	10°C <t<20°c< td=""></t<20°c<>
±5%	for	T<10°C

Our dewpoint instruments account for the sensor specific version of the surface plot directly via a look up table.

NOTE: Convert the observed output voltage to %RH values via the first equation before applying the second equation.

CONDENSATION AND WETTING

CONDENSATION occurs whenever the surface temperature of the sensor's active area drops below the ambient dew point of the surrounding gas. Condensation forms on the sensor (or any surface) even if the surface temperature only momentarily drops below the ambient dew point. Small temperature fluctuations near the sensor can unknowingly cause condensation to form when operating at humidity levels above 95%.

While quick to condense, water is slow to evaporate in high humidity conditions (i.e. when the surface temperature of the sensor is only slightly above the ambient dew point.) Because of this, a sensor's recovery period from either condensation or wetting is much longer than its normal time response. During recovery, the sensor outputs a constant 100% RH signal regardless of the ambient RH.

When an application calls for continuous monitoring of RH at humidity levels of 90% and above, take steps to avoid intermittent condensation. Some strategies are:

- 1. Maintain a good air mixing to minimize local temperature fluctuations.
- The HIH-3602-A and -C use a sintered stainless steel filter to protect the sensor from splashing. A hydrophobic coating further suppresses condensation and wetting in rapidly saturating and de-saturating or splash prone environments.
- 3. Heat the RH sensor so that the active area is hotter than the local dew point. This can be done through an external heater or by self heating of the CMOS RH chip by operating it at a higher supply voltage.

NOTE: Heating an RH sensor above ambient temperature changes its calibration and makes it sensitive to thermal disturbances such as air flow. When contemplating such an approach, MICRO SWITCH recommends selecting an HIH-3602 type sensor and getting application technical support.

INTEGRATED SIGNAL CONDITIONING

All RH sensors quickly recover from condensation or wetting with no shift in calibration. However, after 24 hour or longer exposures to either high >95% RH or continuous condensation, an upward shift of 2% to 3% RH may occur. This shift is repeatable and can be reversed by placing the sensor in a low 10% RH environment for a 10 hour period.

Silicon integrated humidity sensors (RHIC – relative humidity integrated circuit) incorporate signal conditioning circuitry onchip with the sensing capacitor. These "RHIC" humidity sensors are laser trimmed so that at $V_{supply} = 5$ V, the output voltage typically spans 0.8V to 3.9V for the 0% RH to 100% RH range at 25°C. (Sensor specific calibration data printouts and best fit lines at 25°C are either included or available as an option on every sensor.)



The HIH-3602-C incorporates a RHIC humidity sensor, a 1000Ω platinum RTD and anti-static protection in a single TO-5 can.

RHIC based sensors are factory calibrated, micro-power devices with either individual calibration and/or good unit-to-unit interchangeability. These features help OEM manufacturers avoid in-house humidity calibration costs and extend battery life in portable instruments. Improved accuracy can be obtained by tuning system electronics to account an individual sensors Best Fit Line at 25°C.



when accounting for the sensor specific data.

System performance when relying on sensor interchangeability.

HUMIDITY SENSOR CHEMICAL RESISTIVITY

Humidity sensors are routinely exposed to chemically active environments in the process of making moisture measurements. Chemical resistivity is an important differentiate between competing sensors and resulting system accuracy and reliability. To address this, MICRO SWITCH always uses proprietary, chemically resistive and thermally stable thermoset polymer as the active medium in all of its humidity and moisture sensors.

While following data reflects testing on the HIH-3602 sensor, the results are indicative of all other MICRO SWITCH moisture sensors. Protocols are severe relative to typical applications.

SATURATION AND RECOVERY PROTOCOL

- For each chemical tested, seven HIH-3602 sensors calibrated at 0% and 75.3% RH.
- A chemical saturation test was done by placing a drop of chemical on top of the sensor completely covering the hydrophobic filter for 175 minutes. A blow dryer was then applied to reduce the RH reading from 100% back down to room ambient.
- The sensors were again tested at 0% and 75.3% RH.
- The sensors are next allowed to recover under ambient RH for 60 hours.
- The sensors are again tested at 0% and 75.3% RH.

SATURATION & RECOVERY RESULTS

	Post Saturation		Post Recovery	
Chemical	∆% at 0% RH	∆% at 75.3% RH	∆% at 0% RH	∆% at 75.3% RH
Alcohol Isopropyl, 66%	+0.1	+1.13	+0.0	+1.83
Endo-Spor Hydrogen Peroxide	+0.46	-0.16	+0.4	-0.43
Glutaraldehyde Cydex Plus	+0.56	-2.13	+0.63	-1.63
Idophors Solution Westcodyne	+0.23	+0.16	+0.36	+0.93
Kleenaseptic	+3.13	+4.5	+2.96	+4.66
Quaternary Ammonium Virex 0.2%	+0.43	+0.2	+0.3	+0.8
Sodium Hypochlorite	+0.36	+0.6	+0.43	+1.53

LONG TERM VAPOR EXPOSURE PROTOCOL

- For each chemical tested, three HIH-3602 sensors were suspended 0.75 inches above the liquid chemical surface in a hermetically closed flask.
- Periodically, sensors were removed and tested at 0% RH and 75.3% RH.

Note that an entry of "F" denotes sensor failure. Blank entries indicate that the data was not taken.

LONG TERM EXPOSURE RESULTS

	Δ% RH Change over Exposure Time							
Chemical	89.0 hr		231.5 hr		400.0 hr		893.0 hr	
	0%	100%	0%	100%	0%	100%	0%	100%
Ammonia Hydroxide	F	F	F	F	F	F	F	F
Acetone	F*	F	F	F	F	F	F	F
Ethanol	F	F	F	F	F	F	F	F
Methanol	-1.9	25.1	-1.9	29.4	-3.7	35.0	-5.4	39.8
50% Ethanol + 50% Methanol	14.5	-17.4			7.8	-31.8	4.2	-22.0
Formaldehyde hyst. grade	0.8	0.0	1.5	-0.3	1.5	-1.4	1.9	-3.5
Formaldehyde neutral soln.	0.6	-0.7	1.2	-2.0	1.1	-3.5	1.6	-6.1
Formaldehyde norm & buff'd	0.4	0.8	1.2	-0.4	1.1	-1.3	1.5	-3.2
Benzene	-2.0	1.5	-1.1	-1.7	-0.3	-8.1	-1.1	-24.7
Toluene	-1.7	1.4	-0.8	0.4	0.4	0.0	-0.9	-4.3
Xylene	-1.7	1.5	-0.8	-0.2	-0.6	-0.7	-0.9**	0.0 ²
30% Benzene + 30% Toluene + 40% Xylene	-03	-1.2			-0.1	-6.0	-0.6	-16.1

*Sensors are resistant to acetone over shorter exposures

**One sensor failed.

PSYCHROMETRICS & MOISTURE

MOISTURE measurements involve different terms and units. Moisture terms and units all fall under the area of psychrometrics, the study of water vapor concentration in air as a function of temperature and pressure. Selecting a moisture term depends on the application at hand.

Dew points and frost points are often used when the dryness of the gas is important, (moisture condensation from gas at low process temperatures must be avoided). Dew point is also used as an indicator of water vapor in high temperature processes, such as industrial drying.

Mixing ratios, volume percent, and specific humidity are usually used when water vapor is either an impurity or a defined component of a process gas mixture used in manufacturing. Mixing ratios are also used, like dew point, in industrial drying.

Relative humidity is most commonly used in HVAC applications where it directly impacts human comfort and indoor air quality issues. Relative humidity is also of interest to process control personnel as low RH can cause brittleness and static electricity problems, while high RH can cause swelling and clumping regardless of temperature.

Term	Definition	Unit	
Absolute Humidity, (Vapor concentration)	Mass, Vapor Volume	Grains/ft³ Grams/m³	
Mixing Ratio	Mass, Vapor Mass, dry gas	lb/lb, grains/lb, kg/kg, grams/kg	
Relative Humidity	Mass, actual vapor Mass saturated vapor Actual vapor pressure Saturation vapor pressure Partial pressure, vapor Vapor pressure water	%	
Dew Point	Temperature of saturation (condensation)	°F or °C	
Volume Ratio	Partial pressure, vapor Partial pressure, dry gas	% by volume	
Mass Ratio	Same as Mixing Ratio	PPM by weight, PPM _w	
PPM by volume	Volume, vapor x 10 ⁶ Volume, dry gas	PPM by volume, PPM _v	
PPM by weight	$PPM_{v} \times \frac{Mole \ weight \ of \ water}{Mole \ weight \ of} \\ carrier \ gas$	PPM by weight, PPM _w	
Hygrometer	Instrument for measuring moisture in gas (from Greek hygros – wet, moist)		
Psychrometer	Instrument using wet/dry bulbs to measure moisture in gas (from Greek psychros – cold)		

MOISTURE TERMS, DEFINITIONS AND UNITS

PSYCHROMETRICS deals with the thermodynamic properties of moist gases while the term **Humidity** simply refers to the presence of water vapor in air or other carrier gas.

Psychrometrics concerns mixtures of water vapor and dry air. Much of it also applies to other carrier gases since the thermodynamic characteristics of water vapor are fairly independent of the carrier gas. In addition, as the composition of atmospheric air is fairly constant, dry air is treated as a homogeneous gas with a molecular weight of 28.9645. The molecular weight of water is 18.01528.

PARTIAL PRESSURE: The gas laws say that the total pressure of a gas mixture is the sum of the partial pressures of the constituent gases. Also the volume ratios of constituent gases are equal to the ratios of their partial pressures. For example, atmospheric pressure is the sum of the partial pressures of dry air and water vapor ($\rho_{atm} = \rho = \rho_a + \rho_w$).

WATER VAPOR PRESSURE: When a mixture of air and water vapor is in equilibrium with liquid water or with ice, it is considered to be saturated (RH = 100%). The water vapor saturation pressure over ice for the temperature range of -148 to 32° F is given by:

$$\begin{split} & \text{In}(\rho_{\text{WS}}) = \quad \frac{C_1}{T} \quad + C_2 + C_3 T + C_4 T^2 + C_5 T^3 + C_6 T^4 + C_7 \,\text{In}(T) \\ & \text{where} \quad C_1 = -1.0214165 E + 04 \quad C_5 = 3.5575832 E - 10 \\ & C_2 = -4.8932428 E + 00 \quad C_6 = -9.0344688 E - 14 \\ & C_3 = -5.3765794 E - 03 \quad C_7 = 4.1635019 E + 00 \\ & C_4 = 1.9202377 E - 07 \end{split}$$

The saturation pressure over *liquid water* for the temperature range of 32 to 392°F is given by:

$$\ln(\rho_{WS}) = \frac{C_8}{T} + C_9 + C_{10}T + C_{11}T^2 + C_{12}T^3 + C_{13}\ln(T)$$

where
$$C_8 = -1.0440397E + 04$$
 $C_{11} = 1.2890360E - 05$
 $C_9 = -1.1294650E + 01$ $C_{12} = -2.4780681E - 09$
 $C_{10} = -2.7022355E - 02$ $C_{13} = 6.5459673$

In both of the above equations,

 ρ_{ws} = saturation pressure, psia

T = absolute temperature, $^{\circ}R = ^{\circ}F + 459.67$

SIMPLIFIED FORMULATIONS: The preceding equations are very accurate, but may be overly cumbersome for real time calculation. The following equations are less accurate, but are generally suitable for mid-range calculations as used in HVAC applications, for example.

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For dew points higher than ice point:

$$e = [1.0007 + P \times 3.46E - 6] \times 6.1121 \times \exp\left(\frac{17.502 \times T}{240.9 + T}\right)$$

For dew points at or below ice point:

$$e = [1.0003 + P \times 4.18E - 6] \times 6.1115 \times \exp \left| \frac{22.452 \times T}{272.55 + T} \right|$$

- $e \gg p_w$ vapor pressure in millibars
- (one psi = 68.94745 millibars) P = total pressure in millibars (1 atm = 1013.25 millibars, 14.696 psia)
- T = temperature in $^{\circ}C(^{\circ}F = ^{\circ}C \times 1.8 + 32)$

RELATIVE HUMIDITY: the ratio of the partial vapor pressure to saturation vapor pressure at the dry bulb temperature:

$$\mathsf{RH} = \frac{\rho_{\mathsf{w}}}{\rho_{\mathsf{ws}}} = \frac{\rho_{\mathsf{ws}}(\mathsf{T}_{\mathsf{d}})}{\rho_{\mathsf{ws}}(\mathsf{T})}$$

where $\rho_{\rm WS}(T_d)$ is saturation pressure at the dew point temperature and $\rho_{\rm WS}(T)$ is saturation pressure at the dry bulb temperature. Relative humidity is moisture and temperature dependent but independent of total pressure. If dew point and dry bulb temperatures are known, then RH can be derived by calculating saturation vapor pressure for dew point and for dry bulb, then applying the RH definition above.

DEW POINT is the temperature at which a given sample of moist air is saturated. If the sample is cooled below dew point, then water vapor begins to condense. This phenomenon is the basis for various chilled sensor type dew point meters.

Frost Point: If measurements are made below the freezing point of water – that is if the indicated dew point is below the freezing point of water, then the equilibrium occurs at the vapor pressure of ice (not water), which is less than that of water. That is, the frost point is a bit higher than dew point.

If RH and dry bulb temperature are known, dew point can be derived by first calculating saturation pressure at the dry bulb temperature and then multiplying by the RH ratio to obtain ρ_w , the partial water vapor pressure. Now apply the following:

For the dew points in the range of 32 to 200°F:

$$T_{d} = C_{14} + C_{15}\alpha + C_{16}\alpha^{2} + C_{17}\alpha^{3} + C_{18}\rho_{W}^{0.1984}$$

And for dew points below 32°F:

 $T_{d} = 90.12 + 26.412\alpha + 0.8927\alpha^{2}$

Where for both expressions:

$T_d = dew point, °F$	$\alpha = \ln(\rho_w), \rho_w$ in psia
$C_{14} = 100.45$	$C_{15} = 33.193$
$C_{16} = 2.319$	$C_{17} = 0.17074$
$C_{18} = 1.2063$	

VOLUME RATIO (also called mixing ratio by volume, or ppmv) is the ratio of water vapor volume to dry air volume (V_w/V_a). Because the volume ratios of mixed gases are the same as their partial pressures, volume ratio can be expressed as:

$$\mathsf{VR} = \frac{\rho_{\mathsf{W}}}{\rho_{\mathsf{a}}}; \rho = \rho_{\mathsf{W}} + \rho_{\mathsf{a}}$$

Because total pressure is the sum of partial pressures, the partial pressure of dry air can be readily derived (once vapor pressure is known), by measuring total pressure directly or by assuming one atmosphere (14.696 psia) total pressure. Multiply the ratio by one million to obtain ppmv (parts per million by volume).

HUMIDITY RATIO (also called mixing ratio by weight, or ppmw) is the ratio of the mass of water vapor to the mass of dry air. To calculate this, multiply the volume ratio by the ratio of the molecular weights:

$$W \equiv \frac{M_w}{M_a} = \frac{18.01528 \ \rho_w}{28.9645 \ \rho_a} = 0.62198 \ \frac{\rho_w}{\rho_a}$$

The humidity ratio, in common use, is expressed in lb/lb, grains/ lb, kg/kg, or g/kg. (There are 7000 grains in one pound.) Multiply the ratio by one million to obtain ppmw (parts per million by weight). An engineer may, for example, combine a humidity ratio value with the reading from a mass flow meter to calculate the mass of water vapor flowing through a dryer exhaust duct per unit time.

VOLUME PERCENT: equivalent to 100 times the mole fraction; the ratio of water vapor volume to total volume, V_w/V or $V_w/(V_w + V_a)$ expressed as a percentage. Like the volume ratio, it can be calculated in terms of partial pressures:

$$\mathsf{V\%} = \frac{\rho_{\mathsf{W}}}{\rho}; \rho = \rho_{\mathsf{W}} + \rho_{\mathsf{a}}$$

SPECIFIC HUMIDITY: normally expressed as a percentage, is the ratio of the mass of water vapor to the total mass, and can also be calculated in terms of the humidity ratio:

$$q = -\frac{M_w}{M_w + M_a} = -\frac{W}{1 + W}$$

ABSOLUTE HUMIDITY: (or water vapor density) is the ratio of the mass of water vapor to the total volume:

$$d_v = \frac{M_v}{V} = \frac{217.6 \times e}{T_{db} + 273.16}$$

 d_v = absolute humidity expressed in grams H₂O per cubic meter of dry air and vapor mix (divide by 16,018.46 for lb/cu ft; divide by 2.28835 for grains/cu ft)

 $e = \rho_w$ vapor pressure in millibars (1 psi = 68.94745 millibars)

 T_{db} = dry bulb temperature in °C (°F = °C × 1.8 + 32)

ENTHALPY: the measure of the energy content per unit mass. The enthalpy of a gas mixture equals the sum of the individual partial enthalpies of the components, (dry air and water vapor). In the English system, the specific enthalpy of dry air is assigned a value of zero at 0°F and standard atmospheric pressure. To calculate moist air enthalpy in Btu/lb dry air:

$$h = 0.240T + W(1061 + 0.444T)$$

where

- T = dry bulb temperature, °F
- W = humidity ratio of the moist air

STANDARD ATMOSPHERIC DATA: Normal atmospheric pressure variations have small effects on calculations that require a value for total pressure. However, at higher altitudes (Denver, for example), atmospheric pressure variations become significant. The following standard data is adapted from NASA. At sea level, standard temperature is 59°F and standard barometric pressure is 29.921 in. Hg.

STANDARD	ATMOSPHERIC	PRESSURE D	ΔΤΔ
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Altitude	Temp.	Pressure		
ft	°F	in Hg.	psia	
0	59.0	29.921	14.696	
500	57.2	29.38	14.430	
1000	55.4	28.86	14.175	
2000	51.9	27.82	13.664	
3000	48.3	26.82	13.173	
4000	44.7	25.82	12.682	
5000	41.2	24.90	12.230	

Reference: <u>1993 ASHRAE Handbook of Fundamentals</u>, published by American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1791 Tullie Circle, N.E., Atlanta, GA 30329. Telephone 404-636-8400.

NOTE: Most of the ASHRAE formulations are based on the thermodynamic temperature scale, which differs very slightly from practical scales (ITS-90) used for physical measurements. The boiling point of water is 211.95°F on this scale rather than the traditional 212°F. The slight difference is negligible for any practical application.

SATURATION VAPOR PRESSURES OF WATER P.,

Temperature (°C)	Saturation Vapor Pressure (mmHg)	Temperature (°C)	Saturation Vapor Pressure (mmHg)
-20	0.8	60	149.5
-10	1.9	70	233.8
0	4.6		
10	9.2		
20	17.5		
30	31.8	80	355.3
40	55.4	90	525.9
50	92.6	100	760.0