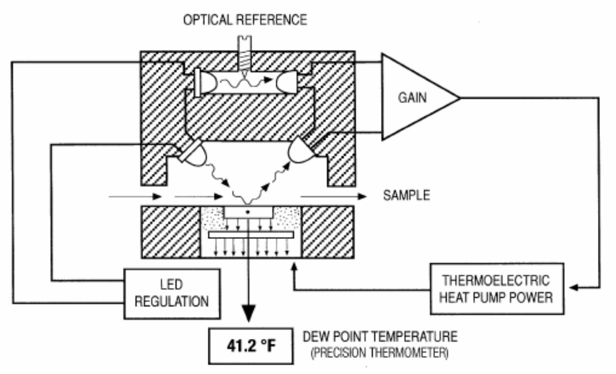
GE Infrastructure
Sensing

The Humilab— NIST Traceable Bench Top Humidity Calibration System

Introduction

GE Infrastructure Sensing's Humilab provides the user with the ability to verify, calibrate and document humidity sensors used in applications in aerospace, automotive, pharmaceutical, electronics, plastics, chemical, food processing/storage and HVAC (Heating Ventilation and Air-Conditioning Controls). The Humilab provides a bench-top environment controlled to stable relative humidity levels by using time-proportional flow control of dry and saturated air streams. The test environment is continuously monitored by a chilled mirror hygrometer, which is a primary NIST traceable humidity standard. The workspace capacity of 644 cubic inches (10.6 Liters) was designed to provide the optimum throughput without sacrificing the ability to be transported on site and function as a standalone humidity calibration system.

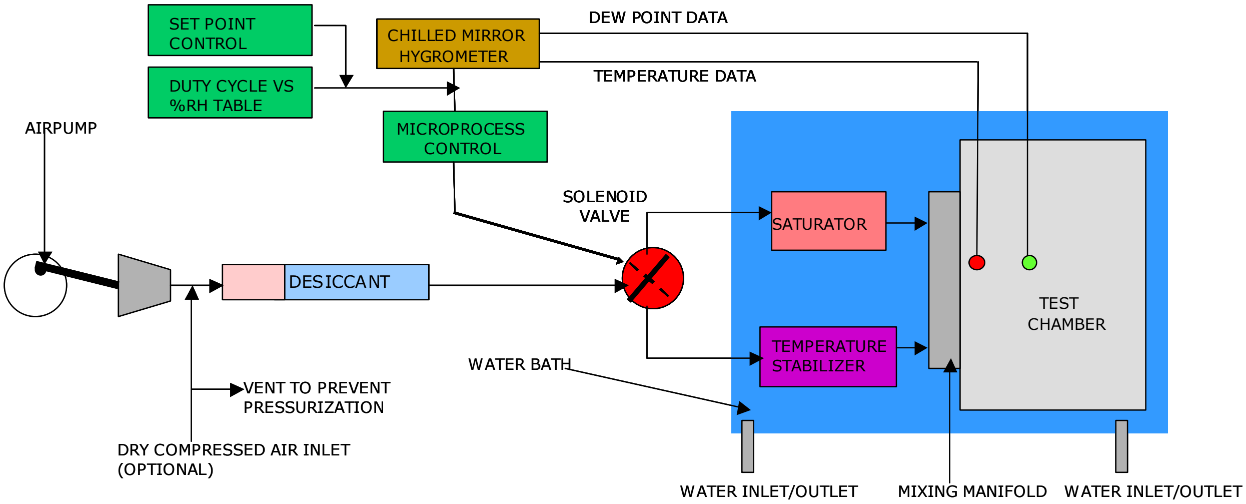


Schematic of Chilled Mirror Sensor

Measuring the Humilab's Test Environment

The Humilab's test environment is measured with a chilled mirror hygrometer. Chilled mirror sensors measure dew point temperature directly by cooling and heating a reflective surface (mirror) by using a thermoelectric heat pump such that a constant mass of dew or frost is maintained. The mirror is made of polished rhodium or platinum. The mirror is illuminated by a GaAs infrared emitter. The control of dew/frost mass is accomplished by using feedback from an optical detector in closed loop control. When the mirror

imagination at work



Schematic of HumiLab divided flow humidity generator/chamber with built-in chilled mirror

is dry, virtually 100% of the signal is received by the photodector. A second emitter/detector pair of is used as a reference. When water condenses on the mirror as dew or frost, the IR light scatters and the decrease in signal is used by a servo-controller to regulate the power and polarity to the thermoelectric heat pump. A precision 4-wire platinum RTD imbedded in the mirror is used to measure the temperature. The mirror temperature, by definition, is equal to the dew/frost point temperature. The system provides fundamental NIST traceable humidity measurement. Since the wetted components of the sensor are inert, chilled mirrors are characterized by having minimal long-term drift. Typical accuracy is ±0.15ºC or better. The dew point measurement along with simultaneous temperature and pressure measurements may be converted by an analyzer to other humidity parameters such as relative humidity, absolute humidity, mass mixing ratio, volumetric mixing ratio, enthalpy and wet bulb.

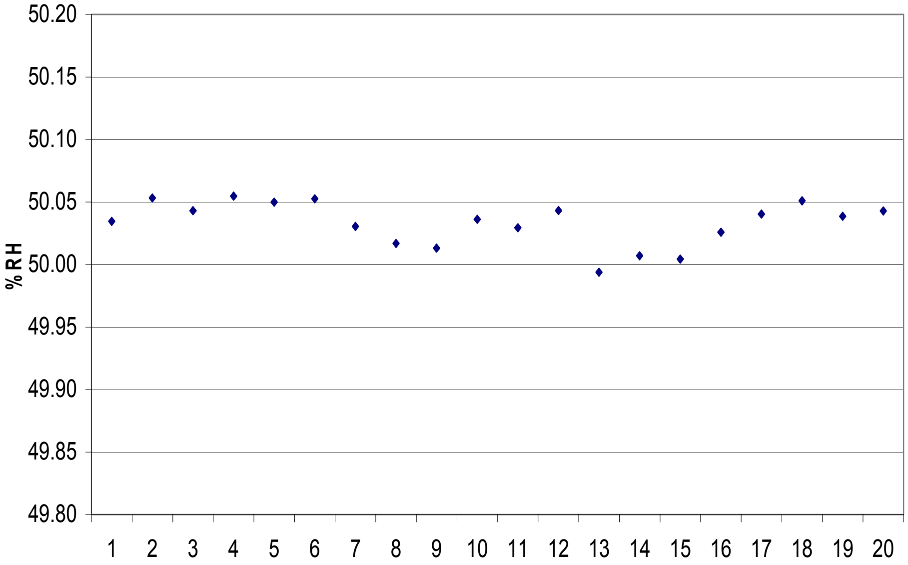
Generating Stable Humidity Values

The Humilab utilizes a fundamental technique to generate stable relative humidity levels. Dry air is mixed with saturated air on a time-proportional basis. The dry air is produced by a desiccant cartridge. The desiccant is calcium sulfate with a cobalt chloride indicator. When cobalt chloride is dry or anhydrous, it is a vivid blue color. When hydrated it turns pink. The saturated air is produced by sparging (bubbling air) through water. If the dry air and saturated air are conditioned to the same temperature, the volumetric ratio produces a relative humidity which obeys the following equation:

$$\textbf{(1)}\quad \mathbf{RH_m = \frac{V_d RH_d + V_s RH_s}{V_d + V_s}}$$

RH_m = Relative Humidity of the Mixture
RH_d = Relative Humidity of Dry Air
RH_s = Relative Humidity of Saturated Air
V_d = Volume of Dry Air
V_s = Volume of Saturated Air

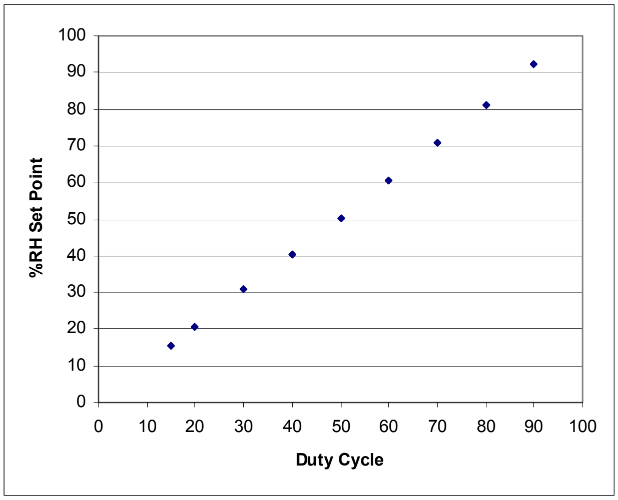
For example; to produce 10 liters/hour of air at 30% RH the volumetric mixing ratio would be 3.0 Liters/hour of saturated air and 7.0 liters/hour of dry air (or a 3:7 volumetric mixing ratio of saturated air to dry air). This is assuming the dry air was completely devoid of water or 0% RH and the saturated air was 100% RH. In practice however, we have measured the dry air produced by the Humilab at an empirical value of –60ºC frost point which is equal to 0.034% RH. The saturator produces an empirical value of 97% RH. If the 3:7 volumetric mixing ratio is maintained the resulting humidity would be 29.3% RH. We could adjust the mixing ratio slightly to produce 30% RH by making a measurement of the test environment with a precise humidity instrument and adjusting the mixing ratio. The Humilab's built in chilled mirror hygrometer and control algorithm performs those functions. The chamber may be operated in two modes:



The stability of the Humilab has been conformed to better than ±0.2% RH. The plot above shows control at 50% RH and 25°C.

%RH Set Point	Duty Cycle
15	15.3
20	20.6
30	30.7
40	40.2
50	50.2
60	60.6
70	70.8
80	81.2
90	92.3

The duty cycle of the Humilab is calibrated against the chilled mirror at 9 points . "Break point" linear regression is used in the control algorithm to determine the duty cycle for each set point. In closed loop control, after 20 minutes of operation, the duty cycle is adjusted by 1/2 the difference between the actual %RH and the set point every 5 minutes.



Open Loop—The volumetric mixing ratio between dry air and air from the saturator is fixed.

Closed Loop—The volumetric mixing ratio between dry air and air from the saturator is adjusted based on feedback from a chilled mirror reference instrument.

In both the open loop and closed loop modes, the test environment is constantly measured with the reference chilled mirror. A 3-way valve is configured to split a dry stream of air between flow through a saturator and a temperature stabilizer. The time duty cycle of the valve will be directly proportional to the volume produced by each flow path. We can substitute the time duty cycle in equation **(1)** as follows:

$$\textbf{(2)} \quad \mathbf{RH_m = \frac{DC_d RH_d + DC_s RH_s}{DC_d + DC_s}}$$

DCd = Time Duty Cycle of Dry Air
DCs = Time Duty Cycle of Saturated Air

Since the sum of the dry air duty cycle and saturated air duty cycle is unity, the equation can be further simplified to:

$$\textbf{(3)} \quad \mathbf{RH_m = DC_d RH_d + DC_s RH_s}$$

Furthermore, since the $\mathbf{RH_d}$ term is close to zero, the relative humidity of the mixture is mainly a function of $\mathbf{DC_s}$ (the duty cycle of the saturated air).

Time Based Control is Repeatable

The key to the stable and repeatable humidity generation of the Humilab is that the measurement of time is highly repeatable. A quartz servo-lock digital timer produces highly reproducible water vapor mixing ratios. The Humilab is calibrated by running the chamber in an automated “ramp and soak” profile in a process that dwells at 9 set points. A fixed dwell time is established for each set point and the chamber’s %RH is adjusted until the actual %RH of the chamber matches the set point. The set point vs. time duty cycle to achieve the desired %RH condition is stored in an electronic look up table. In operation, the duty cycle for any given set point is calculated using linear regression **(y = mx+b)** based on the interval bound by two successive calibration points.

Feedback Control from the Chilled Mirror

Generating humidity by using time-proportional control in the open-loop control mode would not by itself be a suitable reference standard. The user would have no way of verifying that the test environment has reached a stable value. In order to confirm the humidity of the environment, a chilled mirror and temperature sensor (Platinum RTD) is placed directly in the chamber. The net result of the “open loop” control is that the generated %RH value within the chamber will not necessarily match the set point. There might be some degree of offset. The advantage of open loop control is the response time to achieve stable %RH conditions with be faster than in closed loop control. Empirically, about 20% faster.

In “closed loop” control the %RH reading of the chilled mirror hygrometer is used to adjust the time duty cycle. In the Humilab’s “closed loop control” mode the chamber is run in “open loop” for the first 20 minutes after a given set point is selected. Once a stable %RH is achieved, adjustments of 1/2 of the difference between the actual humidity and the set point are made to the duty cycle every 5 minutes. In this algorithm, small corrections are made resulting in the %RH of the chamber matching the set point to within ±0.2% RH or better.

The Key to %RH Control is Temperature

The precise and repeatable control of relative humidity is highly dependent on temperature stability. Relative Humidity (%RH) is defined as:

$$(4) \quad \%\mathrm{RH} = \frac{e}{e_s} \times 100$$

%RH = Percent Relative Humidity
e = partial pressure of water vapor
$\mathbf{e_s}$ = saturation water vapor pressure

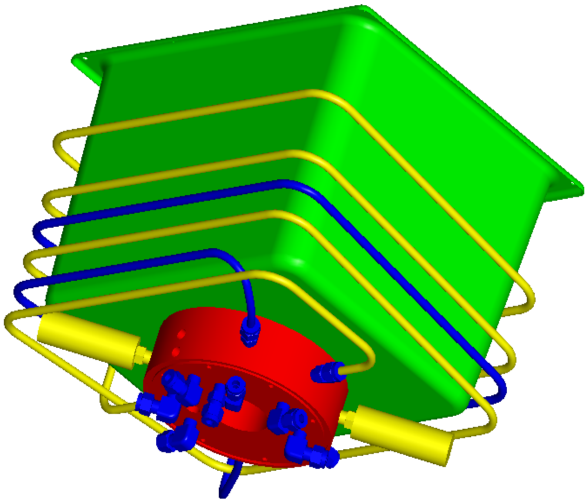
The saturation water vapor pressure is defined as the partial pressure that water would have to exert in a system at a specific temperature to fully saturate the space. Any water vapor in excess of this value will condense into liquid. The following equation computes the saturation water vapor pressure based on temperature and the prevailing atmospheric pressure:

$$(6) \quad e_s = (1.007 + 3.46E-6 \times P) \times 6.112 EXP(\frac{17.502T}{240.97+T})$$

$\mathbf{e_s}$ **=** Saturation Water Vapor Pressure (mbar)
T = Temperature (ºC)
P = Total Pressure (mbar)

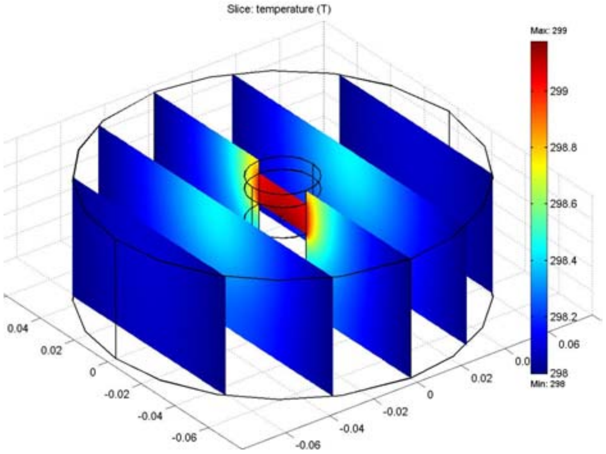
When $\mathbf{e=e_s}$ the relative humidity is 100% RH. The value **e** can also be computed from equation (**6**) by substituting **T** with the dew point temperature (**Td)**. The dew point temperature is defined as the temperature a parcel of gas would have to be cooled to in order to saturate the space. In addition, any plane vibration free surface that is at or below the dew point temperature will acquire a condensation layer. The latter concept is an integral part of the theory of humidity or dew point measurement using a condensation hygrometer such as a chilled mirror.

It is apparent from equation **(6)** that temperature plays a significant role in the saturation pressure value. At 25ºC the saturation vapor pressure = 31.68 mbar. If the temperature changes by -0.1ºC, the saturation vapor pressure changes to 31.50 mbar about 0.6%. In a relative humidity calibration system operating at 25ºC an error or variance of 0.1ºC will affect the %RH by about 0.6% of the reading.



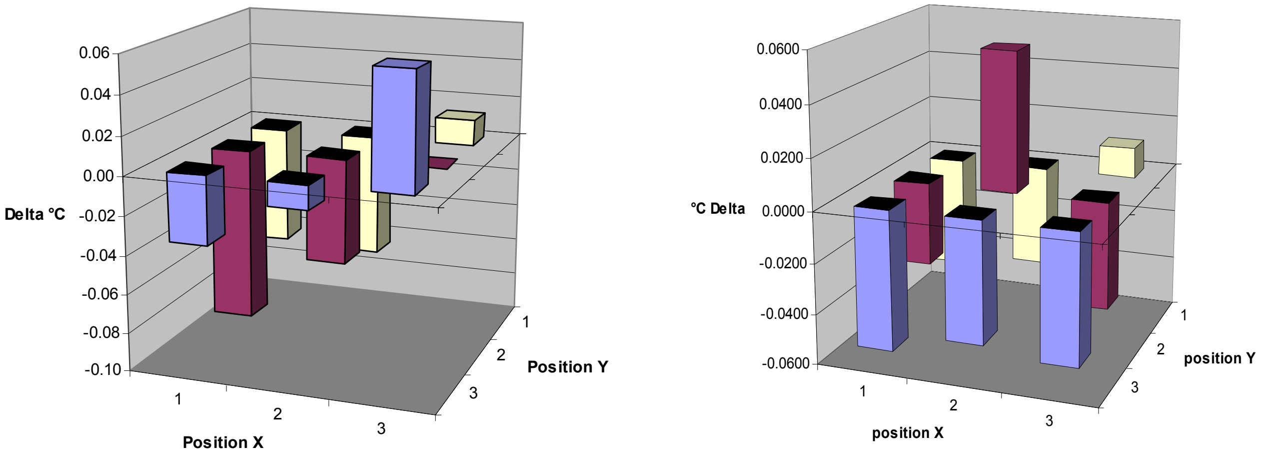
The HumiLab's stainless steel test chamber is immersed in a water bath. The air supplied to the chamber is temperature conditioned via a coil immersed in the bath. An I/O block houses the chilled mirror sensor. An external bath/circulator may be used to circulate temperature controlled water through a coil immersed in the water bath to standardize test temperatures.

It is very important that all of the components in a humidity test environment are thermally stable. By placing the test chamber of the Humilab in a water bath, temperature uniformity of better than 0.2ºC is realized. The Humilab's test chamber as well as the saturator and dry air line are all immersed in the same water bath. The walls of the chamber are constructed of stainless steel which has good heat transfer. The water jacket is also surrounded by foam insulation. The chilled mirror sensor installed in the Humilab is a source of heat (a chilled mirror dissipates heat to cool the mirror by the use of thermoelectric cooling). The maximum heat dissipated by the chilled mirror occurs at low %RH values. The chilled mirror is installed in an anodized aluminum I/O block which is immersed in the water bath. This design serves to dissipate the heat very efficiently. The thermal characteristics of the chamber was modeled using Femlab software. Based on the materials used, mass, surface area, ambient temperature and specific heat, the software predicts a temperature rise of less than 0.6ºK at the maximum heat dissipation of the chilled mirror. A DOE (design of experiment) was conducted to verify the thermal uniformity. The workspace was three-dimensionally zoned into 18 locations. A temperature controlled water bath/circulator was used to circulate temperature controlled water though the Humilab's water jacket. A calibrated PRTD (Platinum Resistance Temperature Detector) was used to measure the temperature in each of the zones. Since the same PRTD was used, the reproducibility is very high and a very good map of the thermal gradient was obtained. The data confirms that the thermal gradient was well within 0.2ºC.



Thermal modeling software was used as a design tool to predict the heat dissipation of the chilled mirror. The test chamber system has thermal gradients of less than ±0.1ºC

The Humilab utilizes a Lexan cover to facilitate feed-throughs for a wide variety of humidity sensors and probes. The Lexan cover is sufficiently thick to provide adequate insulation at room temperature. At elevated or lower temperatures there may be heat loss or gain through the cover. The surface temperature of the Lexan cover limits the humidity setting of the Humilab. The dew point temperature the chamber cannot equal or exceed the temperature of the Lexan cover or water will condense on it.



Thermal gradient maps of the HumiLab test chamber . The map at the left is 3" below the cover and the map at the right is 6" below the cover

The Humilab is a bench top humidity calibrator that can be transported on site, filled with about 2.2 gallons of water (8.3 liters), plugged into AC power (120 or 240 VAC) and used almost immediately. Since it is equipped with an onboard desiccant cartridge to produce dry air, the unit is self-contained. Without a temperature bath/circulator, the temperature of the test chamber will be dependent on the ambient temperature. Since a PRTD is installed in the chamber, the temperature is continuously monitored. The insulated water jacket and Lexan cover provides sufficient thermal mass and insulation that changes are slow and this facilitates the calibration of many types of humidity sensors. After the Humilab is filled with water, one should allow sufficient time for the temperature to stabilize, particularly if the water has not been at room temperature or the Humilab is brought in from a hot or cold environment (car trunk). For calibrations where a standardized temperature is required, the use of a temperature bath/circulator is recommended.

Accuracy

The accuracy of calibrations performed in the Humilab is based on three fundamental sources of error:

1. Dew Point measurement of chilled mirror
2. Dry Bulb temperature measurement of the reference PRTD
3. Thermal gradient between the DUT (device under test) and the reference PRTD.

The chilled mirror fundamentally measures dew point and dry bulb temperature and calculates the relative humidity. Note that the thermal gradient error is based on the difference between the temperature at the DUT and the reference PRTD; not the thermal difference between the DUT and the chilled mirror sensor. The chilled mirror measures dew point, which is a function of the partial pressure of water vapor. In a closed system pressure equalizes, therefore the dew point is uniform throughout the chamber. Because temperature is a measurement of the kinetic energy of matter, air at hotter temperatures is more buoyant (i.e. hot air rises) causing temperature stratification. One method of destratifying air is to create air movement. This can be accomplished with fans, however electrical motors give off parasitic heat. The Humilab has air movement due to the workspace air being constantly vented from the chamber and replaced by humidity controlled air. The nominal flow rate is 4 Liters/min and since the workspace volume is 10.6 liters there are 22.6 air changes per hour. Based on the thermal models the main factor in keeping the test chamber thermally stable is the surface area of the stainless steel walls. The walls in turn are stable due being water jacketed on 5 of the 6 contact surfaces of the chamber.

The uncertainty table above gives an error analysis of the HumiLab. All of the contributing values are converted to the same unit; %RH. The 1-sigma and 2-sigma values are statistical probabilities with 1-sigma covering 68% confidence and 2-sigma providing 95%

Relative Humidity Error Analysis of the HumiLab

%RH	Temperature (C)	Dew Point (C)	%RH Error for Dew Point	%RH Error for Dry Bulb	% RH Error for Gradient	1 Sigma (RSS)	2 Sigma
5.00	25.00	-15.46	0.07	0.04	0.03	0.09	0.17
10.00	25.00	-7.75	0.13	0.09	0.06	0.17	0.34
20.00	25.00	0.50	0.22	0.18	0.12	0.31	0.62
30.00	25.00	6.24	0.31	0.27	0.18	0.45	0.90
40.00	25.00	10.47	0.40	0.35	0.24	0.58	1.17
50.00	25.00	13.86	0.49	0.45	0.30	0.73	1.46
60.00	25.00	16.70	0.58	0.53	0.30	0.84	1.68
70.00	25.00	19.15	0.66	0.62	0.42	1.00	2.00
80.00	25.00	21.46	0.74	0.71	0.48	1.13	2.26
90.00	25.00	23.24	0.82	0.80	0.54	1.27	2.53
95.00	25.00	24.14	0.86	0.85	0.57	1.34	2.67

Humilab Error Analysis Based on:
±0.15°C Dew Point Accuracy of Chilled Mirror
±0.15°C Dry Bulb Accuracy of Dry Bulb PRTD
±0.1°C Temperature Gradient

All of the sources of errors are converted to %RH. Statistically it is not probable that all the errors will manifest in the same direction ; therefore the RSS (root sum square) is a better approximation of system uncertainty assuming the error distribution is normal. The RSS or 1-sigma provides a 68% confidence while 2-sigma provides 95% confidence.

confidence. Each HumiLab however is calibrated against a NIST traceable chilled mirror reference standard to a tolerance of:

±1.0% RH from 10-70% RH from 20-30ºC
±1.5% RH from 70-90% RH at 20-30ºC

A certificate of calibration with the functional test data is supplied.

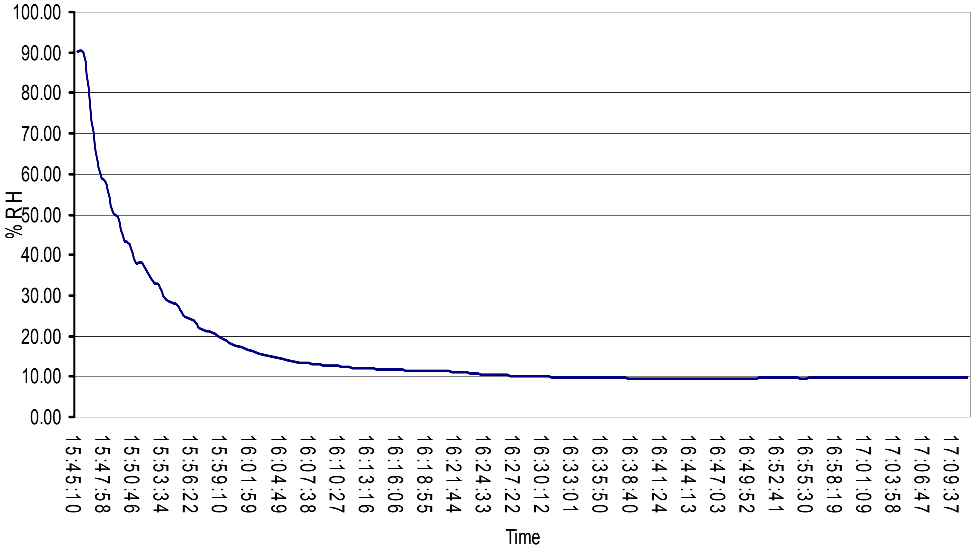
Ramp & Soak Control & Data Logging

The Humilab is provided with Prostep software which enables “Ramp and Soak” profiles to be run. The profiles are programmed in Prostep then uploaded to the Humilab via a RS-232 port. The Humilab does not have “guaranteed soak”, therefore it is up to the user to program enough time for the chamber to stabilized at a given set point. The ramp and soak feature is ideal for calibrating data loggers and recorders and also facilitates automated calibration.

Prostep also features simple to use data logging software. The humidity and temperature data from the Humilab is streamed via the RS-232 port and saved as time stamped ASCII delimited text. This enables the data to be opened in standard spreadsheet programs such as Excel for further analysis and graphing. To the Metrologist data recordings of standards used for calibration are a valuable tool. The data can graphically show parameters such as response time, hysteresis, overshoot, and stability. Collecting the data via RS-232 is advantageous because the digital data stream provides greater confidence than analog signals which may be subject to signal loss or induction from electrical fields. The HumiLab also provides analog outputs of the reference data (4-20mA & 0-5VDC) which are calibrated against the digital data. The other obvious advantage of recording data from the Humilab is unattended operation.

Humidity Calibration Takes Time

Humidity calibration takes “time” for all of the elements to stabilize. This includes the calibration apparatus as well as the devices under test. While many humidity probes report response time of 1-tau (63% step change) in the orders of magnitude in seconds, the full artifact inside the chamber must achieve both thermal and moisture equilibrium. Full stability at a given set point should be allotted 30-40 minutes at a minimum and optimally at least 1 hour.



Response time of the Humilab from 90-10% RH. The time-constant (1-tau or 63% step change) is about 4.5 minutes.

About GE Infrastructure Sensing

GE General Eastern is part of the GE Infrastructure Sensing business, is a recognized global leader in humidity, temperature, flow, gas analysis and pressure measurement.

GE Infrastructure Sensing is an industry leader in the design and manufacture of multiple sensing elements, devices, instruments and systems that enable our customers to monitor, protect, control and ensure the safety of their critical applications. GE's comprehensive sensing offerings includes precision sensors for temperature, pressure, humidity, gas, infrared and ultrasonic applications; as well as high-quality handheld and portable field calibrators, stand alone measurement instrumentation and systems that provide the end-to-end solutions necessary to verify, validate or certify vital processes.

With operations around the world, GE Infrastructure Sensing develops technologies and solutions using thermal validation, dew point measurement, ultrasonic and gas flow measurement, control circuit protection, liquid level detection, process control instrumentation, and microstructure design for products and services in applications such as environmental, marine, meteorology, aerospace, defense, medical, pharmaceutical, biotechnology, automotive, industrial, commercial, petrochemical, power generation and transportation.

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