GE General Eastern Instruments

The Humilab— Bench Top NIST Traceable Humidity Calibration System

Introduction

GE General Eastern's Humilab provides the user with the ability to verify, calibrate and document humidity sensors used in applications in aerospace, automotive, pharmaceutical, electronic, 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 transfer 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 stand-alone humidity calibration system.

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 a reflective surface using thermoelectric cooling until a dew or frost layer condenses on the surface. The surface is made of either polished rhodium or platinum. The temperature of the mirror maintained such that the mass of water vapor condensing and evaporating is at an equilibrium. This is accomplished by incorporating feedback control loop from an optical detector. The polished surface of mirror is illuminated by a GaAs infrared emitter. When the mirror is dry, virtually 100% of the signal is received by a 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 control to regulate the power to the thermoelectric cooling module. A precision 4-wire platinum RTD imbedded in the mirror block is used to measure the temperature which is, by definition, equal to the dew/frost point temperature. The system provides fundamental NIST traceable humidity measurement. Since the wetted components of the chilled mirror sensor are inert, the sensor is characterized by having minimal long-term drift. Typical accuracy is ±0.2ºC 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 temperature.

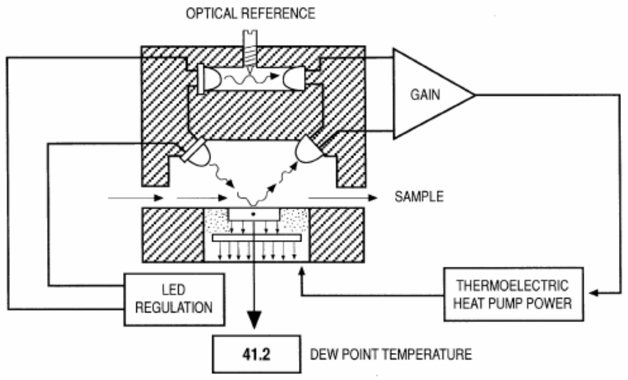


Figure 1. Schematic of Chilled Mirror Sensor

Generating Stable Humidity Values

The Humilab utilizes is simple technique to generate stable levels of relative humidity. 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 Chloride 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 (or near saturated air) is produced by sparging (bubbling air) through water. If the dry air and saturated air are conditioned to the same temperature then the volumetric ratio of saturated air mixed to the dry air produces a resulting

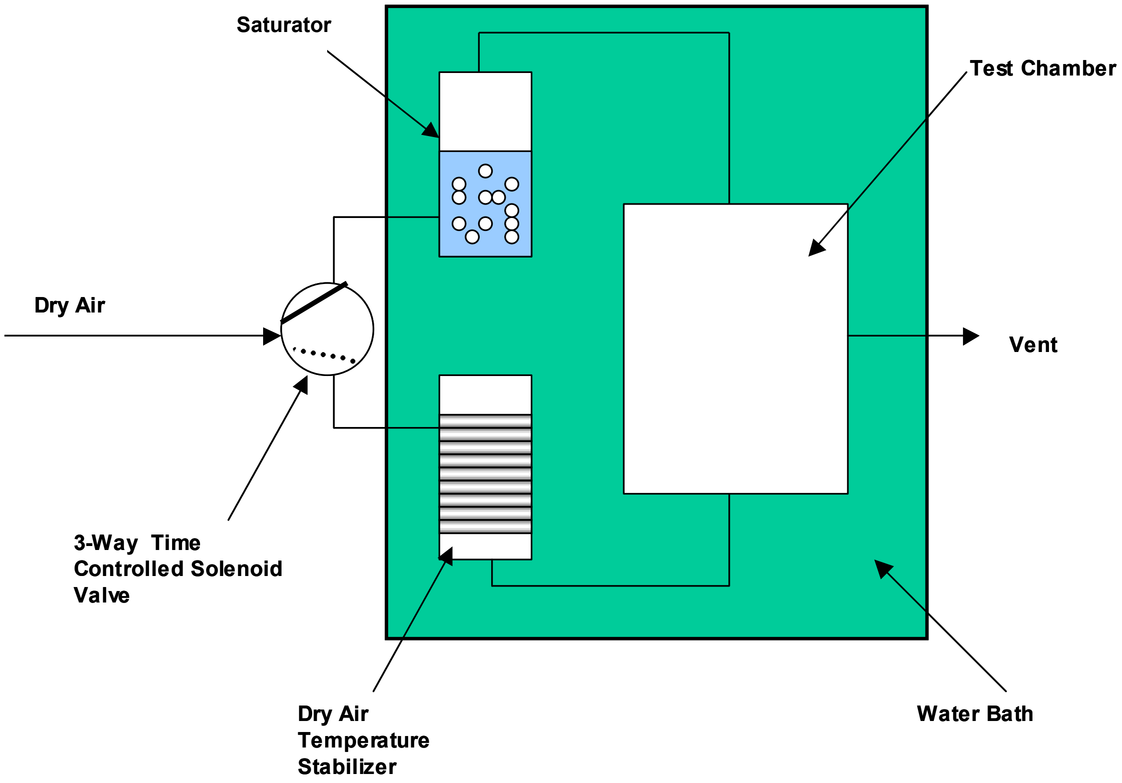


Figure 2. Schematic of Time Proportional Humidity Generator used by the Humilab

relative humidity which obeys the following equation:

(1) $$\%RHm = \frac{Vd \times \%RHd + Vs \times \%RHs}{Vd + Vs}$$

RHm = Relative Humidity of the Mixture
RHd = Relative Humidity of Dry Air
RHs = Relative Humidity of Saturated Air
Vd = Volume of Dry Air
Vs = Volume of Saturated Air

To produce 10 liters of air at 30% RH the volumetric mixing ratio would be 3.0 Liters of saturated air and 7.0 liters of dry air (or a 3:7 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 mix ratio is maintained the resulting humidity would be 29.3% RH. We could adjust the mixing ratio slightly to produce an 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 performs both functions and the chamber may be operated in two modes;

> **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 cases the test environment is constantly measured with the reference chilled mirror.

If a 3- way valve is configured to split a dry stream of air between flow through a saturator and a temperature stabilizer where the time duty cycle is controlled, the time duty cycle through the respective paths will be directly proportional to the volume. (See **Fig. 1**) We can substitute time constants or duty cycle in equation **(1)** as follows:

(2) $$\%RHm = \frac{DCd \times \%RHd + DCs \times \%RHs}{td + ts}$$

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

The equation can be further simplified to:

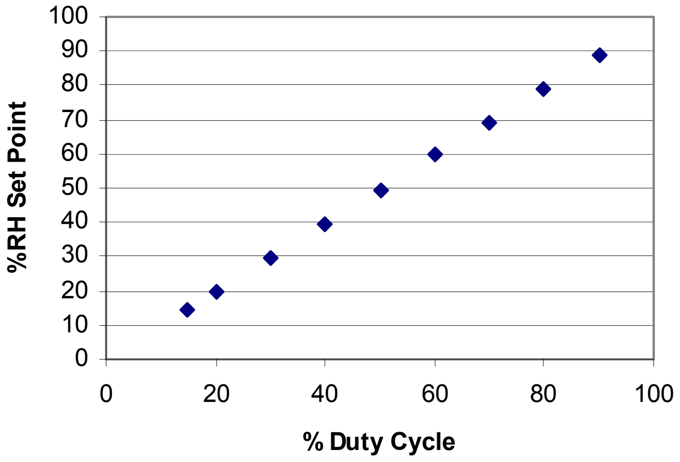
(3) $$\%RHm = DCd \times \%RHd + DCs \times \%RHs$$

Since the sum of the dry air duty cycle and saturated air duty cycle is unity. Furthermore, since the **RHd** term is close to zero, the relative humidity of the mixture is mainly a function of **DCs**.

(4) $$\%RHm = f(DCs)$$

The key to the stable and repeatable humidity generation of the Humilab is that the measurement or time is highly repeatable. A low cost quartz servo-lock digital timer will produce 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 condition of the chamber matches the set point . The Humilab's microprocessor control system waits until a fixed number of successive readings do not vary by more than 0.2% RH. 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.



Set Point (%RH)	% Duty Cycle
15	14.3
20	19.6
30	29.7
40	39.2
50	49.2
60	59.6
70	69.2
80	79.1
90	88.9

Figure 3. Typical Humilab calibration values stored in humidity generator look up table. Linear regression between two successive calibration points is used to determine the time duty cycle for a given set point.

Feedback Control from the Chilled Mirror

Generating humidity by using a time proportioning control in open open-loop control would not by itself be a suitable reference standard because the user has 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 open loop control the built in reference chilled mirror hygrometer monitors the chamber environmental conditions for the duration of the calibration process.

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" the chamber is run in "open loop" for the first 20-30 minutes after a given set point is selected. Once a stable %RH is achieved, a correction to the duty cycle of 1/2 of the difference between the actual humidity and the set point is made. In this manner small corrections are made resulting in the %RH of the chamber matching the set point to within ±0.2% RH.

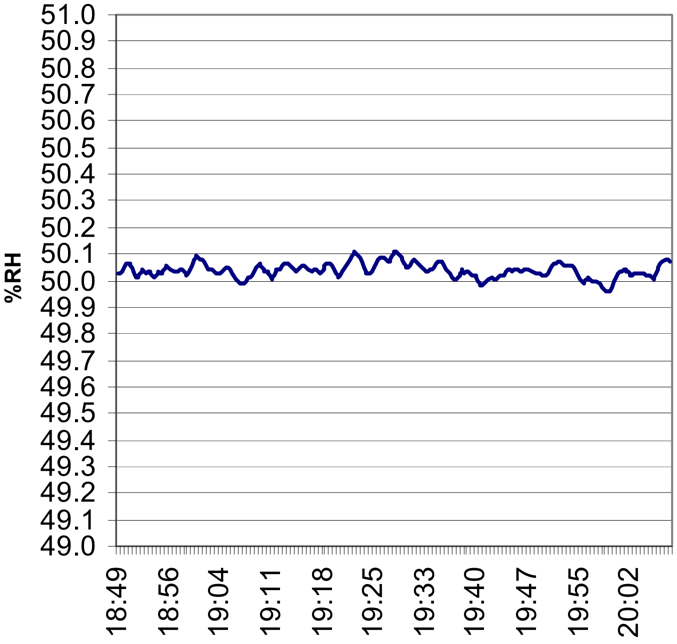


Figure 4. Typical closed loop control. Set point of 50% RH at 25ºC. The Humilab is designed to provide stability of ±0.2% RH or better.

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:

$$(5)\ \%RH = \frac{e \times 100}{es}$$

%RH = Percent Relative Humidity
e = partial pressure of water vapor
es = 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 atmospheric pressure:

$$\textbf{(6)}\ es = (1.007 + 3.46E\text{-}6 \times P) * 6.112EXP\ \frac{17.502T}{240.97 + T}$$

es = Saturation Water Vapor Pressure (millibars)
T = Temperature (ºC)
P = Total Pressure (millibars)

When **e=es** the relative humidity is 100% RH. The value **e** can also be computed from equation **(5**) by substituting **T** with the dew point temperature (**Td)**. The dew point temperature can be 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.

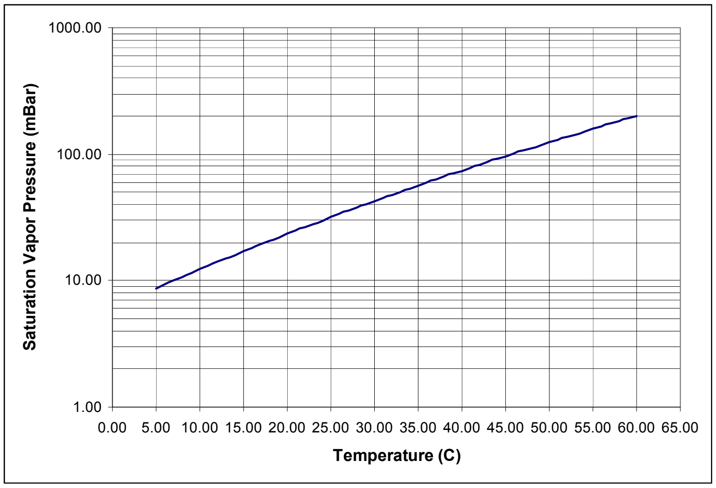


Figure 5. Saturation water vapor pressure vs. temperature

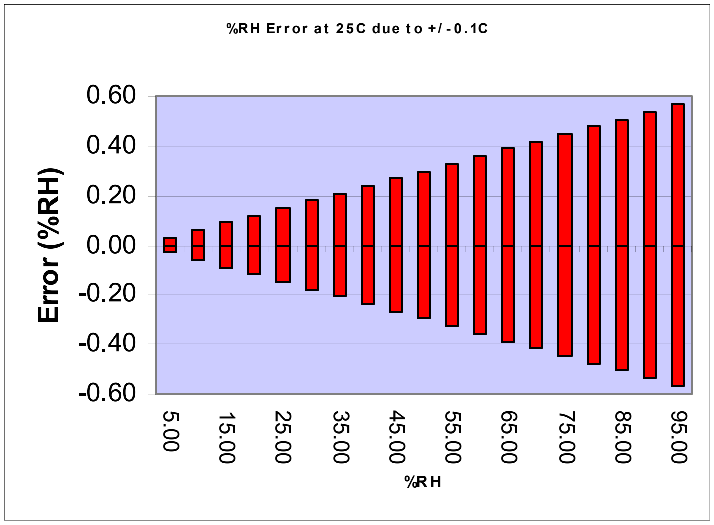


Figure 6. %RH error due to temperature measurement

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 or about 0.6% change. In a relative humidity calibration system operating at 25ºC an error or variance of 0.1ºC will effect the %RH by about 0.6% of the reading. **Figure 6.** shows the error bands in %RH measurement due to a 0.1ºC variance in the dry bulb temperature. The magnitude of error would also be the same for each 0.1ºC difference between a reference temperature sensor and a humidity device under test (DUT) and approximately the same for each 0.1C error in dew point temperature. 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 temperature conditioner are all immersed in the same water bath. The walls of the chamber are constructed of stainless steel which has very 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 and dry air is a better "heat sink" than moist air. In addition the heat generated from the chilled mirror is constant when the test environment is stable. The chilled mirror is installed in an anodized aluminum I/O block with also has ports for water circulation and the air inlet to the test chamber as well as being surrounded by water. 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. The walls of the chamber and water bath provide excellent temperature uniformity and negate thermal gradients.

A DOE (design of experiment) was conducted to verify the test chamber's thermal uniformity. The workspace was three dimensionally zoned into 16 regions. A laboratory temperature controlled laboratory bath/circulator was used to circulate temperature controlled water though the Humilab's water jacket. A calibrated PRTD was used to measure the temperature in each of the 16 work zones. Since the same RTD was used, the reproducibility is very high and a very good map of the thermal gradient was obtained. The experiment confirms that the thermal gradient was within 0.2C.

The Humilab utilizes a Lexan cover to facilitate feed-throughs

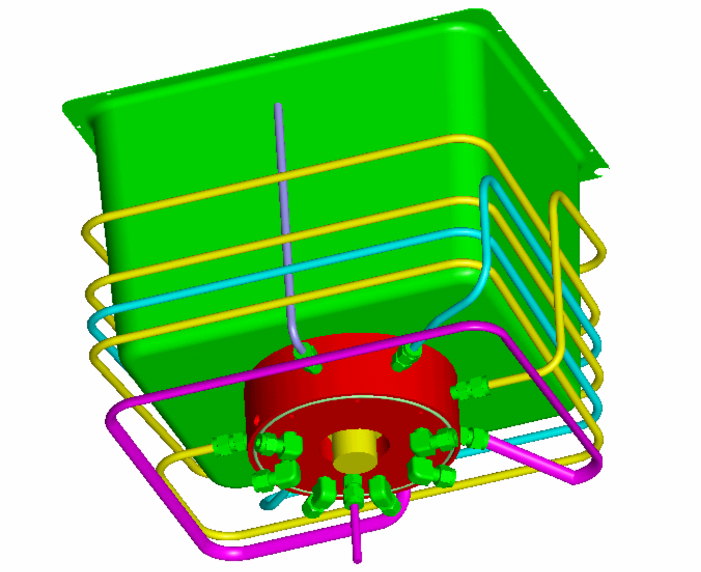


Figure 7. Inner stainless steel chamber with aluminum sensor housing. The chamber is immersed in a water bath.

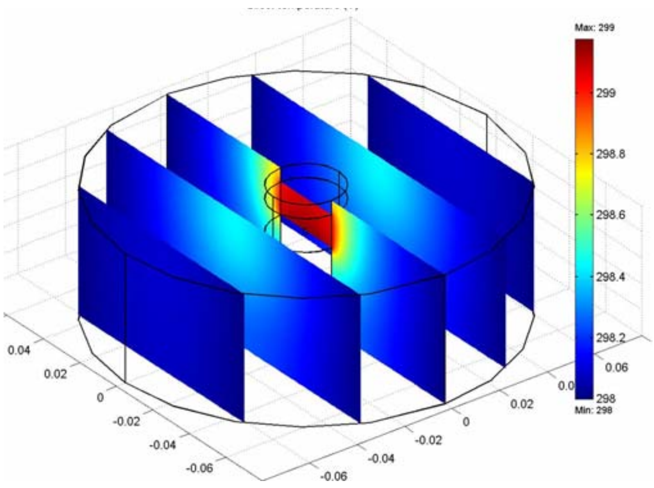


Figure 8. Thermal gradient model of chilled mirror heat dissipation. Modeled by Femlab software.

Figure 8. Temperature controlled bath/circulator used to circulate water through the water bath of the Humilab.

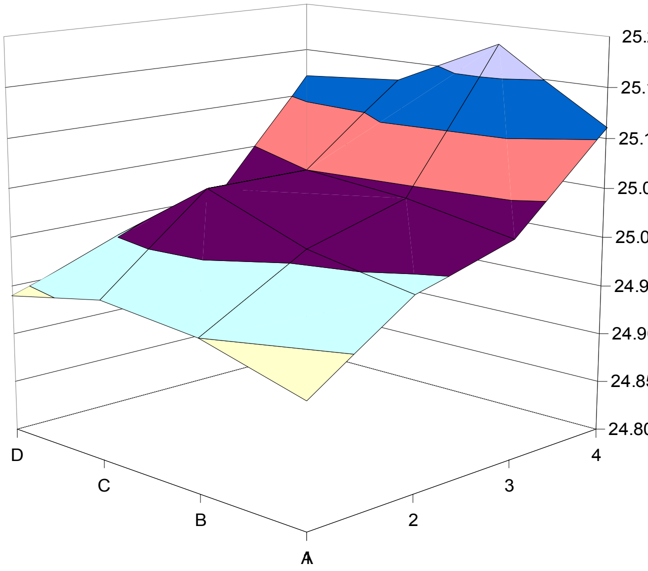


Figure 10. Thermal gradient map of Humilab. 16 zones were measured and the spread was within 0.2C.

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. Further testing will be conducted at various temperatures with an insulated cover which is under development.

The humidity setting of the Humilab is limited by the surface temperature of the Lexan cover. The dew point temperature of air in the chamber cannot equal or exceed the temperature of the Lexan cover or water will condense on it. If the cover is heated, it cannot be excess of the chamber's environment as this would cause a thermal gradient. Additional goals of the development of the insulated or heated cover is to solve this issues. The challenge is to design a cover which tracks the temperature of the test chamber and that allows artifacts under test to be fed through it.

Transportability

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 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, once should allow sufficient time for the temperature to stabilize,

%RH	Temperature (C)	Dew Point (C)	%RH Error for Dew Point	%RH Error for Dry Bulb	% RH Error for Gradient	Alger-braic Sum	1 Sigma	2 Sigma
5.00	25.00	-15.46	0.07	0.04	0.03	0.14	0.09	0.17
10.00	25.00	-7.75	0.13	0.09	0.06	0.28	0.17	0.34
20.00	25.00	0.50	0.22	0.18	0.12	0.52	0.31	0.62
30.00	25.00	6.24	0.31	0.27	0.18	0.76	0.45	0.90
40.00	25.00	10.47	0.40	0.35	0.24	0.99	0.58	1.17
50.00	25.00	13.86	0.49	0.45	0.30	1.24	0.73	1.46
60.00	25.00	16.70	0.58	0.53	0.30	1.41	0.84	1.68
70.00	25.00	19.15	0.66	0.62	0.42	1.70	1.00	2.00
80.00	25.00	21.46	0.74	0.71	0.48	1.93	1.13	2.26
90.00	25.00	23.24	0.82	0.80	0.54	2.16	1.27	2.53
95.00	25.00	24.14	0.86	0.85	0.57	2.28	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

Figure 11. Error analysis of the Humilab

particulary 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 temperatures 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:

- Dew Point measurement of chilled mirror
- Dry Bulb temperature measurement of the reference PRTD
- 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. 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 measure of the kinetic energy, 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 liters there are 20 air changes per hour. Based on the thermal models however, 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.

Figure 11. provides a table of the error stack up of the chamber. All of the contributing values are converted to the same unit; %RH. The algebraic sum of errors gives the worse case based on the measurements being within specifications. The 1-sigma and 2-sigma values are statistical probabilities with 1-sigma covering 68% confidence and 2-sigma providing 95% confidence.

The Humilab is calibrated against a NIST traceable chilled mirror reference standard to a tolerance of:

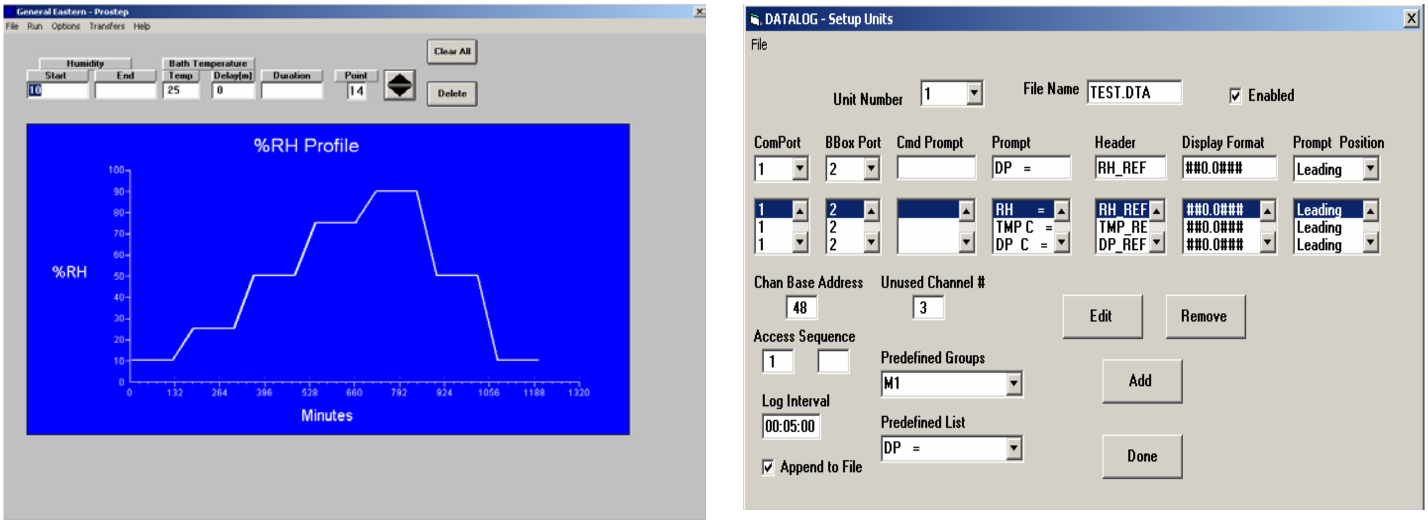
- ±1.5% RH from 10-80% RH from 20-30ºC
- ±2% RH from 80-90% RH at 25ºC

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 is also is also supplied with data logging software. The data from the Humilab is streamed via the RS-232 port and



Humidity Start: 10
Humidity End:
Bath Temperature Temp: 25
Bath Temperature Delay(m): 0
Duration:
Point: 14

Unit Number: 1
File Name: TEST.DTA
☑ Enabled
ComPort: 1
BBox Port: 2
Cmd Prompt:
Prompt: DP =
Header: RH_REF
Display Format: ##0.0###
Prompt Position: Leading

ComPort	BBox Port	Cmd Prompt	Prompt	Header	Display Format	Prompt Position
1	2		RH =	RH_REF	##0.0###	Leading
1	2		TMP C =	TMP_RE	##0.0###	Leading
1	2		DP C =	DP_REF	##0.0###	Leading

Chan Base Address: 48
Unused Channel #: 3
Access Sequence: 1
Predefined Groups: M1
Log Interval: 00:05:00
Predefined List: DP =
☑ Append to File

Figure 12. Prostep provides the ability to load ramp & soak profiles as well as data logging to a standard Windows based PC.

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 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.

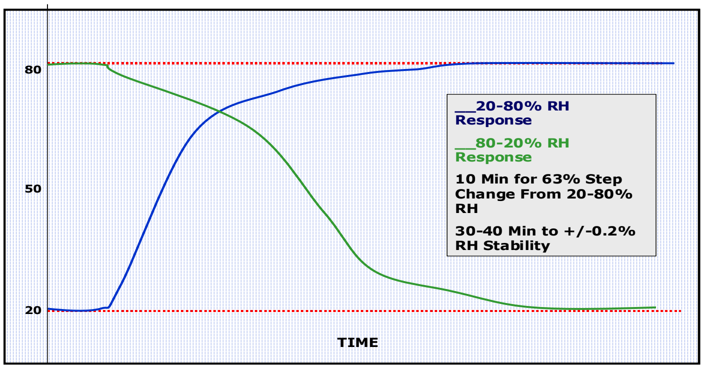


Figure 13. Response time of the Humilab. Less than 10 minutes for 1st tau (63% step change) and 30-40 minutes for full stability.

For additional, technical and pricing information on the Humilab and GE General Eastern's instruments for the measurement of humidity, temperature and pressure, contact our applications engineers or visit our website

www.generaleastern.com

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