Model G9H-2P2T/200

Automated Two-Pressure Two-Temperature
Humidity Generator

RH Systems, LLC

1. Introduction

The G9 Series Precision Humidity Generator is a system capable of continuous, high-accuracy humidity generation over a wide range of humidity, temperature, and flow rates. The G9 design is based on the fundamental two-pressure principle originally developed by NIST. The basis of this principle and its original development are further discussed below.

Background of Humidity Generation

In 1948 at the U.S. National Bureau of Standards (now the National Institute of Standards and Technology), E.R. Weaver and R. Riley developed a “pressure method” for the generation and control of humidity. Their method, termed the *two-pressure principle*, was derived from measurements of temperature and pressure rather than requiring measurements of water vapor.

Using their technique, air or some other gas was saturated with water vapor at high pressure and then expanded to a lower pressure. When saturation and expansion were performed under constant-temperature conditions, the resulting relative humidity of the gas was simply the ratio of the lower pressure to the higher pressure (or at least very nearly).

Their equipment was designed for low rates of gas flow and was used under ambient temperature conditions. Their saturator was a small cylinder containing water and filled with fragments of pumice or stream-washed gravel through which the gas could be bubbled under pressure. This device was developed primarily for the calibration of electrically conductive hygroscopic films used in the measurement of water vapor in gases.

In 1951, also at the National Bureau of Standards, the two-pressure principle was the foundation on which A. Wexler [1] and R.D. Daniels developed a new “pressure–humidity apparatus” with higher air-flow capability. Another significant improvement was the incorporation of temperature control. Developed primarily for hygrometer research and calibration, it was capable of producing atmospheres of known relative humidity from 10 %RH to 98 %RH over a fairly wide temperature range –40°C to +40 °C.

After about twenty-five years of service, this pressure-humidity apparatus was replaced by a newer model, the Mark 2 (which was later referred to as Mark II). This Mark II generator [2] allowed for a wider range of temperature and humidity with improved uncertainty in the generated output.

2. Humidity Generation Principles

Two-Pressure Principle

In an ideal two-pressure system, a stream of gas at an elevated pressure is saturated with respect to the liquid or solid phase of water and then expanded isothermally to a lower pressure. Measurements of the pressure and temperature of the gas stream, both at saturation and after expansion, are all that is required to determine the resulting humidity content of the expanded gas stream. The two-pressure system is shown in Figure 1.

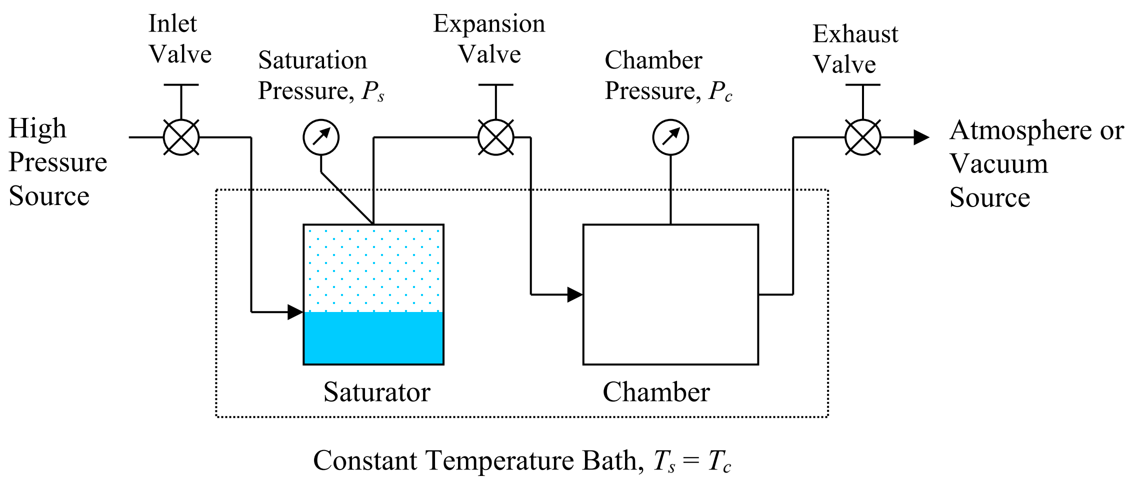


Figure 1—Simplified schematic diagram of the two-pressure principle where $T_s = T_c$.

A two-pressure generator is commonly used in the generation of a range of relative humidity values at fixed temperatures. The saturator and chamber share a common fluid bath temperature and are, ideally, in thermal equilibrium with each other. In this case, the generated relative humidity may be approximated by the ratio of the measured saturated gas-stream pressure (saturation pressure) to the measured chamber pressure by using the simplified expression

$$\text{RH} = \frac{P_c}{P_s} \cdot 100$$

where P_c is the absolute chamber pressure

P_s is the absolute saturation pressure.

Please note that the above expression is only an approximation. More exacting equations are presented below that take into account the non-ideal properties of the water-vapor and the generation technique. When utilizing a two-pressure system, more exacting equations of the hybrid two-pressure two-temperature technique should be strongly considered.

Hybrid Two-Pressure Two-Temperature Principle

The two-pressure principles can be combined with two-temperature principles to form a hybrid system which exhibits and exploits the benefits of both system architectures. In addition to measurement of saturation and chamber pressures, a hybrid system also relies on measurement of saturation and chamber temperatures to fully the resulting humidity. A hybrid two-pressure two-temperature system is shown in elemental schematic form in figure 2.

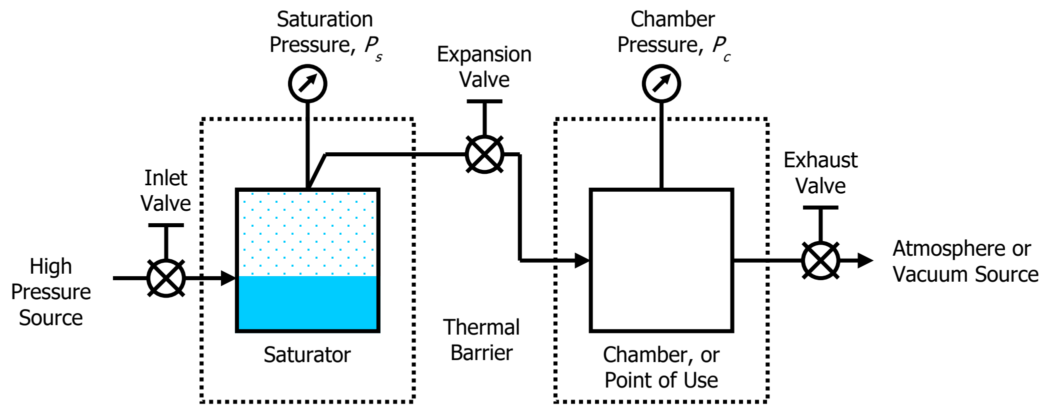


Figure 2—Simplified schematic of the hybrid two-pressure two-temperature where $T_s \neq T_c$.

Here, the temperature of saturation and temperature of the chamber are completely independent and fully accounted for in all equations of humidity. By allowing the saturator and chamber to operate at differing temperatures, a wider variety of humidity values may be generated with reduced requirements on the range of saturation pressure required. The Hybrid two-pressure two-temperature relies on the more exacting equations presented later in this document.

The G9H-2P2T is a hybrid two-pressure two-temperature humidity generator.

3. Common Defining Equations

The following equations of R. Hardy [3] for saturation vapor pressure, enhancement factor, and temperature (from saturation vapor pressure) are common and fundamental to most of the humidity calculations presented here.

Saturation Vapor Pressure over Water

Saturation vapor pressure over *water* at a given ITS-90 temperature in the range –100 °C to +100 °C is defined by the formula

$$e = \exp\left(\sum_{i=0}^{6} g_i T^{i-2} + g_7 \ln T\right) \tag{1}$$

where e is the saturation vapor pressure (in Pascals) over liquid water in the pure phase

T is the temperature in Kelvin

and $g_0 = -2.8365744 \cdot 10^{3}$

$g_1 = -6.028076559 \cdot 10^{3}$

$g_2 = 1.954263612 \cdot 10^{1}$

$g_3 = -2.737830188 \cdot 10^{-2}$

$g_4 = 1.6261698 \cdot 10^{-5}$

$g_5 = 7.0229056 \cdot 10^{-10}$

$g_6 = -1.8680009 \cdot 10^{-13}$

$g_7 = 2.7150305$

Saturation Vapor Pressure over Ice

Saturation vapor pressure over *ice* at a given ITS-90 temperature in the range –100 °C to 0.01 °C is defined by the formula

$$e = \exp\left(\sum_{i=0}^{4} k_i T^{i-1} + k_5 \ln T\right) \tag{2}$$

where e is the saturation vapor pressure (in Pascals) over ice in the pure phase

T is the temperature in Kelvin

and $k_0 = -5.8666426 \cdot 10^{3}$

$k_1 = 2.232870244 \cdot 10^{1}$

$k_2 = 1.39387003 \cdot 10^{-2}$

$k_3 = -3.4262402 \cdot 10^{-5}$

$k_4 = 2.7040955 \cdot 10^{-8}$

$k_5 = 6.7063522 \cdot 10^{-1}$

Enhancement Factor

The "effective" saturation vapor pressure over water or ice in the presence of other gases differs from the ideal saturation vapor pressures given in Equations 1 and 2. The effective saturation vapor pressure is related to the ideal by

$$é = e \cdot f \qquad (3)$$

where *é* is the "effective" saturation vapor pressure

e is the ideal saturation vapor pressure (as given in Equation 1 or 2)

and *f* is the enhancement factor

The enhancement factor, for an air and water-vapor mixture, is determined at a given temperature and pressure from the formula

$$f = \exp\left[\alpha\left(1 - \frac{e}{P}\right) + \beta\left(\frac{P}{e} - 1\right)\right] \qquad (4)$$

with

$$\alpha = \sum_{i=0}^{3} a_i T^i \qquad (5)$$

and

$$\beta = \exp\left(\sum_{i=0}^{3} b_i T^i\right) \qquad (6)$$

where *P* is the total pressure in the same units as *e*

T is temperature in Kelvin

and a_i, b_i depend on temperature range and are given as

for water:

223.15 K to 273.15 K (–50 °C to 0 °C)	273.15 K to 373.15 K (0 °C to 100 °C)
a0 = –5.5898101·10–2	a0 = –1.6302041·10–1
a1 = 6.7140389·10–4	a1 = 1.8071570·10–3
a2 = –2.7492721·10–6	a2 = –6.7703064·10–6
a3 = 3.8268958·10–9	a3 = 8.5813609·10–9
b0 = –8.1985393·101	b0 = –5.9890467·101
b1 = 5.8230823·10–1	b1 = 3.4378043·10–1
b2 = –1.6340527·10–3	b2 = –7.7326396·10–4
b3 = 1.6725084·10–6	b3 = 6.3405286·10–7

for ice:

173.15 to 223.15 K (–100 °C to –50 °C)	223.15 to 273.15 K (–50 °C to 0°C)
a0 = –7.4712663·10–2	a0 = –7.1044201·10–2
a1 = 9.5972907·10–4	a1 = 8.6786223·10–4
a2 = –4.1935419·10–6	a2 = –3.5912529·10–6
a3 = 6.2038841·10–9	a3 = 5.0194210·10–9
b0 = –1.0385289·102	b0 = -8.2308868·101
b1 = 8.5753626·10–1	b1 = 5.6519110·10–1
b2 = –2.8578612·10–3	b2 = –1.5304505·10–3
b3 = 3.5499292·10–6	b3 = 1.5395086·10–6

Temperature from Saturation Vapor Pressure

Equations 1 and 2 are easily solved for saturation vapor pressure over water or ice for a given saturation temperature. However, if vapor pressure is known and temperature is the unknown desired quantity, the solution immediately becomes complicated and must be solved by iteration. For ease of computation, the following inverse equation is provided. This equation is generally used to find the dew point or frost point temperature when the vapor pressure of a gas has been determined. When vapor pressure is known, use the water coefficients to obtain the dew point and use the ice coefficients to obtain the frost point.

$$T = \frac{\sum_{i=0}^{3} c_i (\ln e)^i}{\sum_{i=0}^{3} d_i (\ln e)^i} \qquad (7)$$

where T is the temperature in kelvin

and e is the saturation vapor pressure in pascals

with coefficients

for water:	for ice:
$c_0 = 2.0798233 \cdot 10^{2}$	$c_0 = 2.1257969 \cdot 10^{2}$
$c_1 = -2.0156028 \cdot 10^{1}$	$c_1 = -1.0264612 \cdot 10^{1}$
$c_2 = 4.6778925 \cdot 10^{-1}$	$c_2 = 1.4354796 \cdot 10^{-1}$
$c_3 = -9.2288067 \cdot 10^{-6}$	$c_3 = 0$
$d_0 = 1$	$d_0 = 1$
$d_1 = -1.3319669 \cdot 10^{-1}$	$d_1 = -8.2871619 \cdot 10^{-2}$
$d_2 = 5.6577518 \cdot 10^{-3}$	$d_2 = 2.3540411 \cdot 10^{-3}$
$d_3 = -7.5172865 \cdot 10^{-5}$	$d_3 = -2.4363951 \cdot 10^{-5}$

4. Humidity Equations

The following equations are used in the G9 to calculate various humidity parameters. These equations are not approximations, but rather account for the temperature differences between the saturator and chamber, and the non-ideal behavior of water vapor when admixed with air or other gases.

Relative Humidity

Percent relative humidity is the ratio of the amount of water vapor in a gas to the maximum amount possible at the same temperature and pressure. For two-pressure, two-temperature systems, it is determined by the equation

$$RH = \frac{P_c}{P_s} \cdot \frac{e'_s}{e'_c} \cdot 100 \qquad (8)$$

which then expands to

$$RH = \frac{P_c}{P_s} \cdot \frac{f_s}{f_c} \cdot \frac{e_s}{e_c} \cdot 100 \qquad (9)$$

where P_c is the absolute chamber pressure

P_s is the absolute saturation pressure

f_c is the enhancement factor at chamber temperature and pressure

f_s is the enhancement factor at saturator temperature and pressure

e_c is the saturation vapor pressure at chamber temperature

and e_s is the saturation vapor pressure at saturator temperature.

Dew Point Temperature

Dew point temperature is the temperature to which a gas must be cooled to initiate condensing water vapor in the form of dew (note that dew point temperature can exist above or below 0°C). Dew point temperature is obtained with the following iterative steps.

a. Make an educated guess at the dew or frost point enhancement factor f_d. Setting $f_d = 1$ is a suitable first guess.

b. Next, compute the dew or frost point vapor pressure of the gas with the formula

$$e_d = e_s \cdot \frac{f_s}{f_d} \cdot \frac{P_c}{P_s} \qquad (10)$$

c. Use the dew or frost point vapor pressure e_d determined in the previous step, along with Equation 7 for water, to compute T. Call this value the dew point temperature T_d.

d. Use the dew point temperature T_d, chamber pressure P_c, and Equation 4 for water to compute the dew or frost point enhancement factor f_d.

e. Converge to the proper dew point temperature T_d by repeating steps b through d several times, as necessary.

Frost Point Temperature

Frost point temperature is the temperature to which a gas must be cooled to begin condensing water vapor in the form of frost or ice. Frost point exists only at temperatures below freezing. Frost point is obtained with the following iterative steps.

a. Make an educated guess at the dew or frost point enhancement factor f_d. Setting $f_d = 1$ is a suitable first guess.

b. Next, compute the dew or frost point vapor pressure of the gas with the formula

$$e_d = e_s \cdot \frac{f_s}{f_d} \cdot \frac{P_c}{P_s} \tag{10}$$

c. Use the dew or frost point vapor pressure e_d determined in the previous step, along with Equation 7 for ice, to compute T. Call this value the frost point temperature T_f.

d. Use the frost point temperature T_f, chamber pressure P_c, and Equation 4 for ice to compute the dew or frost point enhancement factor f_d.

e. Converge to the proper frost point temperature T_f by repeating steps b through d several times, as necessary.

Vapor Concentration

Vapor-concentration, traditionally referred to as parts per million by volume (ppm_v), is a ratio relating the number of moles of water vapor to the number of moles of the remaining constituents in the gas (the dry gas component). Once established by the following formula, the vapor concentration is insensitive to further changes in pressure or temperature, provided there is no subsequent condensation.

$$\text{vapor concentration} = \frac{f_S \cdot e_S}{P_S - f_S \cdot e_S} \cdot 10^6 \;\; \mu\text{mol/mol} \tag{11}$$

Humidity Ratio

Humidity ratio w is defined as the mass of water vapor to the mass of the dry gas; it is computed with the formula

$$w = \frac{M_w \cdot f_s \cdot e_s}{M_g \left(P_s - f_s \cdot e_s\right)} \;\; \text{g/g} \tag{12}$$

where M_w is the molecular weight of water vapor, 18.02

M_g is the molecular weight of the carrier gas (28.9645 for air).

Humidity ratio may also be computed and expressed in grams per kilogram and micrograms per gram. When expressed in micrograms per gram, humidity ratio is traditionally referred to in parts per million by weight (ppm_w).

Absolute Humidity

Absolute humidity d_v is defined as the mass of water vapor to the unit volume of humidified gas and is computed with the formula

$$d_v = \frac{M_W}{R \cdot T_c} \cdot \frac{f_s \cdot e_s \cdot P_c}{P_s} \quad \text{g/m}^3 \tag{13}$$

where R is the molar gas constant 8.31472

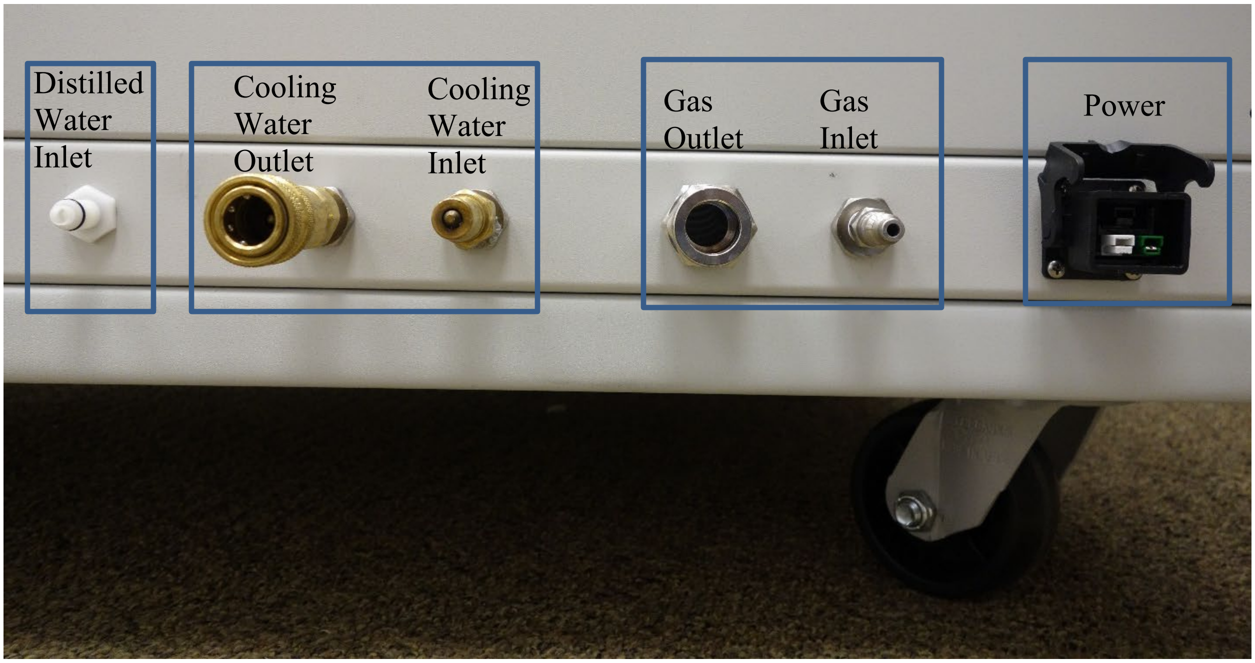
Specific Humidity

Specific humidity q is defined as the mass of the water vapor to the total mass of the gas mixture and is computed with the formula

$$q = \frac{M_W \cdot f_s \cdot e_s}{M_g (P_s - f_s \cdot e_s) + M_W \cdot f_s \cdot e_s} \quad \text{g/g} \tag{14}$$

5. Facility Requirements

Prior arrival of your G9 instrument, preparations should be made to ensure you have the proper facilities available at the desired instrument location. All facility connections are made at the instrument utility panel



Power

The G9 requires 200-230 VAC, 50-60 Hz, single phase power. A transformer is generally not required. Wiring of the AC inputs is generally dependent on the country of installation.

USA, Canada, Mexico, Japan, Taiwan

LINE1, LINE2, GND

where LINE1 and LINE2 are of opposing phase while each is approximately 100-120 VAC with respect to GND

Europe, Asia, Others

LINE, NEUTRAL, GND

where LINE is approx 200-240 VAC with respect to NEUTRAL, with NEUTRAL and GND at the same potential.

Since this system utilizes an open water-filled bath, it is recommended (and may be required by your local electrical codes) to install a Ground Fault Circuit Interrupt (GFCI) breaker at the load center which feeds power to the G9.

Gas Supply

The G9 requires a clean, dry, oil-free, compressed gas source of air or nitrogen. Depending on exact system type, gas should be pre-regulated to a pressure of approximately 150 to 200 psi (1.0 to 1.4 MPa) for the hybrid two-pressure two-temperature system (G9H-2P2T)

Pressure dew point of the gas supply should be 5°C or lower when measured at the regulated pressure. The gas supply should also be capable of supplying a minimum of 100 standard liters per minute.

Cooling Water

Cooling water, although not absolutely required, is recommended. Utilization of cooling water will prevent heat from being dumped into the room air and putting unnecessary strain on the building air conditioning system. Cooling water should be between 10 and 30°C, of a pressure between 15 and 100 psi (100 kPa to 700 kPa), and flow capacity of up to 10 l/min. Water temperature, pressure, and flow do not require regulation. The G9 will internally regulate water flow based on supplied water temperature, water pressure, and G9 cooling demand. The cooling water may be supplied from a recirculating water chiller, or supplied from a standard municipal tap-water outlet.

Waste Water Drain

If cooling water is utilized from a non-recirculating source, waste water from the G9 should be directed to a floor drain or other drain such as a sink.

Distilled Water

The G9 requires a source of distilled water as the source of water vapor for humidity generation. The amount of distilled water required depends on the generated temperature, humidity and flow rate, and the frequency of usage the G9 is subjected to. As a general guideline, maintain at least 5 gallons (20 liters) minimum on hand during use.

Anti-freeze

Approximately 20 liters of alcohol or propylene glycol should be added to the bath / saturator fluid circuits when operating the system below 5 °C.

Floor Space

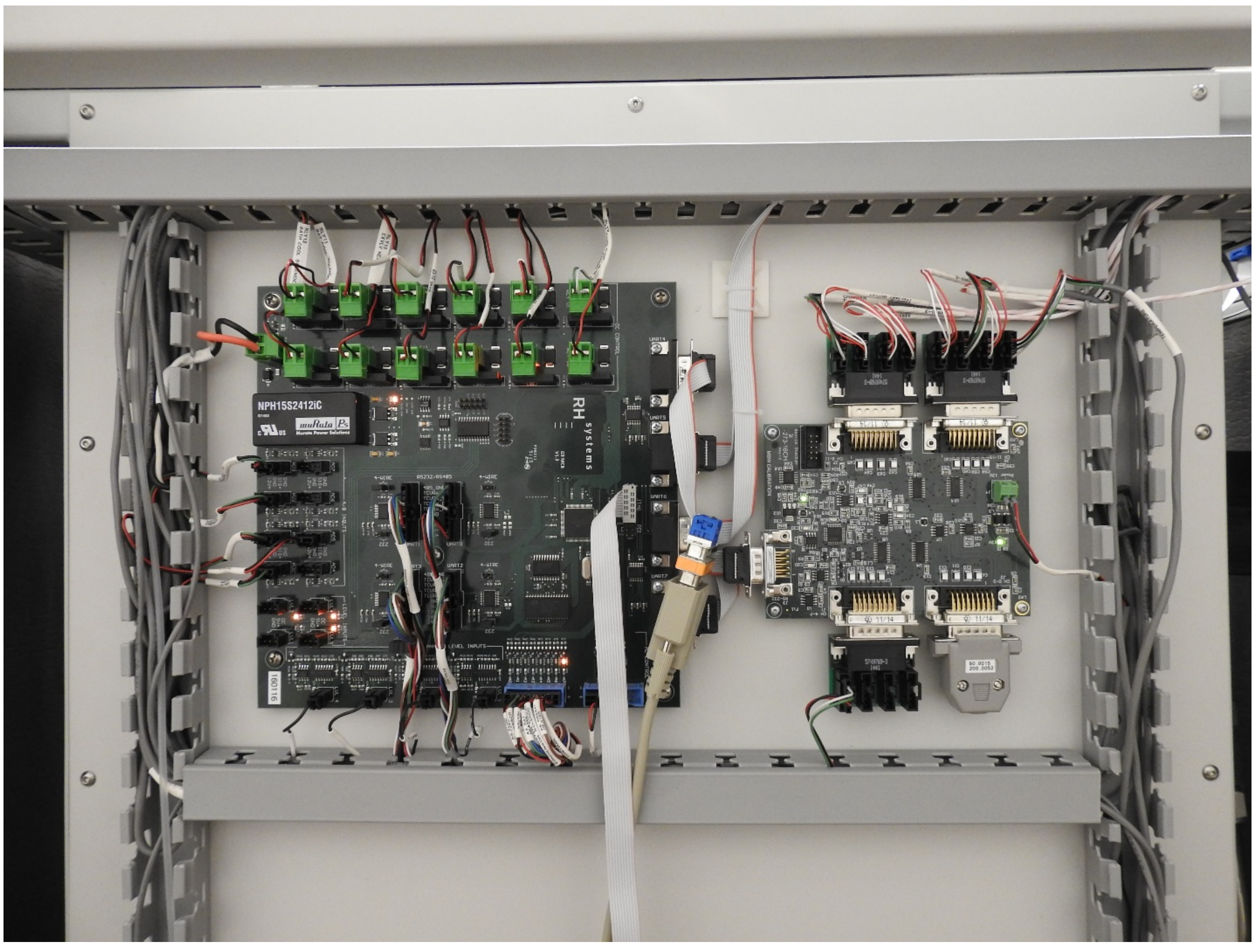
The G9 requires a floor space of approximately 1.5 m x 2 m. This allows adequate space to the sides and rear of the unit for operation, service, and utility connections.

6. Model G9 Sub-Systems

This section provides an overview of the functional systems within the G9. These subsystems include the

- Data Acquisition / Control System
- Pneumatic System (including flow and pressure control)
- Fluid System (including bath and saturator temperature control and liquid levels)
- Electrical System
- Refrigeration System
- User Interface

Data Acquisition / Control System

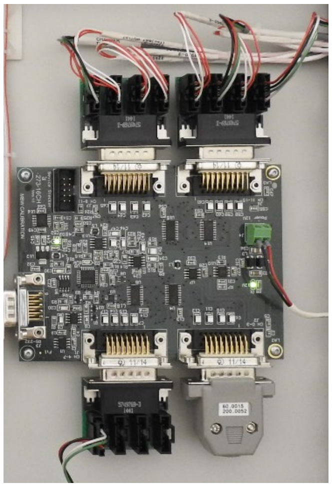


The Data Acquisition / Control Systems of the G9 consists of:

- RHS-T16 embedded, high accuracy, multi-channel temperature measurement system
- G9-GCB embedded controller

RHS-T16 Embedded, High Accuracy, Multi-channel Temperature Measurement System

The RHS-T16 is a 24-bit, high precision, 16 channel, temperature measurement system for use all of the G9 temperature sensors, all of which are 100 ohm platinum resistance thermometers (PRTs). Two (2) of the sixteen (16) channels are configured with ultra-high-precision (UHP) resistors serving as fixed temperature references. Of the remaining channels, there are five temperature measurements with requirements for high precision. These five sensors are installed in the following locations:

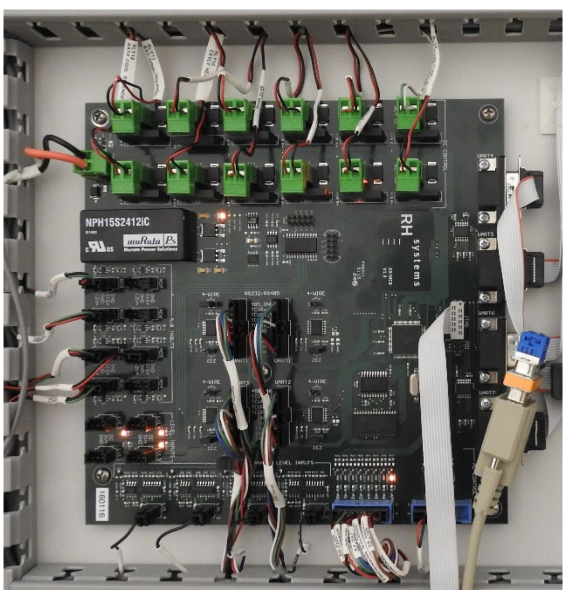


- Bath Fluid
- Test Chamber
- Saturator
- Presaturator
- Expansion Valve

Readings from each of these channels are compared ratio metrically to the two UHP reference resistors, ensuring accurate and stable temperature measurements. The RHS-T16 is fully digital, with all measurements transferred via the serial port to the G9-GCB control system. The RHS-T16 provides for measurement resolution of ±0.001K or better. An RHS-T16 temperature measurement system is utilized in every RH Systems brand humidity generator regardless of model.

G9-GCB Embedded Controller

The G9-GCB embedded controller is a custom designed control system used within all RH Systems brand humidity generators. It performs all functions required for parameter measurement, system control and humidity generation. All valves, relays, pumps, heaters, and other outputs are controlled, and all measurements of temperature (via the RHS T16), pressure, flow, and liquid level are monitored continuously and reported when queried. It communicates to the outside world (for instance, to a PC) through a bidirectional RS-232 serial communication port. Through this port, all control functions are directed, and all measured data is returned.



The G9-GCB has several distinct functional sections:

- Voltage Regulation
- 8-channel Serial I/O ports (RS-232/485)
- 12-channel TTL level digital I/O ports
- 12-channel High voltage digital output ports
- 8-channel hardware driven timer/counters
- 8-channel Analog inputs
- 4-channel Liquid level inputs
- Embedded Firmware

Voltage Regulation

The G9-GCB controller is supplied with 24 VDC from the main G9 system power supply. An on-board DC/DC converter creates isolated +12 VDC for powering analog circuits and transducers such as the pressure sensors and flowmeters. Voltage regulators on-board convert the 24 VDC to +5 VDC for digital functions and liquid level probes. A +3.3 VDC regulator provides power for the CPU and related peripherals.

8-Channel Serial I/O Ports (RS-232/485)

The G9-GCB is designed with either (8) serial ports, four (4) of which operate as RS-232. The other four ports are jumper selectable as either RS-232 or RS-485. When selected as RS-485, they are also jumper selectable as 2 or 4 wire configuration. The serial ports are utilized in the G9 in the following configuration:

1. RS-232 connection to RHS-T16 high-accuracy temperature measurement system
2. RS-232 connection to flow valve control stepper motor
3. RS-232 connection to expansion valve control stepper motor
4. RS-485 connection to flow meter
5. RS-485 connection to high accuracy pressure sensors
6. RS-232 connection to PC for human machine interface
7. RS-232 spare connection to PC, user accessible
8. RS-232 spare connection to PC (generally used as a diagnostic port)

12-Channel TTL Level Digital I/O Ports

The 12-channel TTL level digital I/O ports are individually selectable, on a pin-by-pin basis, as input, output, or bi-directional. In the G9, these are used to drive solid state relays (used for driving high power AC loads such as high power heaters, pumps and compressors), or monitor digital inputs.

12-Channel High voltage digital output ports

The 12-channel high voltage digital output ports are pre-programmed as individually addressable outputs. Each output can source opto-isolated 24 VDC at a current of up to 3 amps per channel. These outputs are used to drive low-to-medium power heaters, pumps, solenoid valves, and relays.

8-Channel Hardware Driven Timer/Counters

The G9-GCB has 8 high-speed, internal, hardware controlled counter/timer channels which are directed via firmware to various digital outputs for high speed pulse width modulation (PWM) control. The high-speed PWM outputs are used in the G9 to drive pressure, flow, and temperature control systems. The precision timing is critical to the overall stability of the G9's various control sub-systems. For slower speed PWM outputs, or less critical timing requirements, software based timer/counters are coupled to any I/O channel (TTL or High-Voltage) in the G9.

8-Channel Analog Inputs

For general purpose variable signal inputs, the 8-channel analog input system is used. These inputs allow for measurement of lower accuracy sensors. There are several low accuracy sensors used to monitor control system status conditions, such as the input supply pressure, refrigeration system pressures, and analog liquid levels. While each of these inputs is required for proper operation of the system, none are used in the control or determination of humidity.

4-Channel Liquid Level Inputs

The G9 requires precise control of liquid levels in the bath, holding tank, and saturator. For each of these precise liquid level requirements, single-point capacitive sensing probes are used. The G9-GCB has the necessary signal conditioning circuitry on-board to convert the small capacitive signals of the liquid level probes to the digital signal levels required.

Embedded Firmware

The G9-GCB embedded firmware runs µC/OS-II, a preemptive real-time operating system (RTOS) that manages up to 255 simultaneous tasks. The µC/OS-II RTOS offers all of the services expected from a modern real-time kernel including resource management, synchronization, inter-task communication, semaphores and message queues. Both the RTOS and G9 embedded firmware are stored in on-board flash memory along with all sensor coefficients and control parameters. The G9 embedded firmware runs all the second-to-second operations required to generate and control humidity. If connected via a serial port, a PC provides a user interface for visualization and storage of generated/controlled parameters.

Pneumatic System

The pneumatic system is responsible for control of gas flow and pressures throughout the system. The pneumatic system consists of the following major components: air inlet circuit, pressure regulator, flow meter, flow control valve, preheater, presaturator, saturator, expansion valve, and chamber.

Compressed air enters the system at the back panel quick-connect fitting. From there it flows to the pressure regulator and a safety relief valve to guard against over pressure at the inlet of the system. The inlet air pressure is measured by the Supply Pressure transducer, *Ps*. The pressure regulator is used to regulate the system pressure, isolating it from upstream variations. The pressure regulator also sets the maximum operating pressure of the system which is then measured by the Regulator Pressure transducer, *Pr*. A mechanical pressure gauge with a needle indication is also connected to this point. Upon leaving the pressure regulator, the gas flows through the air-inlet solenoid. This solenoid is only open during system operation (while generating humidity). During times the system is idle, or the power is off, this solenoid remains closed, removing system pressure from the remaining portions of the system.

During operation, when the Air Inlet Solenoid is activated, the gas then flows through the flow meter and to the flow-control valve. Leaving the flowmeter, the gas then flows through the preheater (to warm the air), through the presaturator (to humidify the air), through the saturator (to precisely stabilize the air temperature and condense out any excess humidity), and finally to the expansion valve. As the high pressure gas from the saturator passes through the expansion valve, it is expanded to a lower pressure, typically ambient pressure. After leaving the expansion valve, the gas passes through a bath-fluid controlled heat exchanger to stabilize the temperature before it flows into the chamber to the devices under test. If the chamber lid is in place and all flanges are sealed, the gas then flows through the chamber outlet, and out through the exhaust port at the back panel. If the chamber lid is not in place, or the access ports are open, the gas generally flows out of the chamber through these open access ports.

Air Inlet Circuit

The air inlet circuit consists of (in pneumatic order) the air inlet fitting, over-pressure relief valve, supply pressure sensor / indicator, supply pressure regulator, and air inlet solenoid.

Mass Flow Transducer

The flowmeter is a thermal mass-flow type meter that transmits its flow measurement readings to the G9-GCB via a serial (RS-232 or RS-485) connection.

Flow Control System

The flow-control valve is a specially designed stepper-motor-driven graduated-orifice-plug (GOP) valve, used for controlling flow rates over eh full range of the generator. To increase system flow rate, the stepper motor will rotate the plug to a position with larger orifice. To reduce the flow rate, the stepper motor will rotate the plug in the opposite direction to a position of smaller orifice. Flow rate is therefore maintained by the rotational position of the plug. The position is controlled by the stepper motor, under control of the embedded controller board, using feedback from the flowmeter.

Preheater

The preheater is used to pre heat the incoming gas to at or near the pre-saturation temperature, easing the thermal load on the presaturator.

Presaturator

The presaturator is a heated pressure vessel containing water and is used to over-saturate the incoming gas. This is accomplished by heating the water in the presaturator to a temperature above that of the saturator. Gas leaving the presaturator will be warmer, and of higher dew point, than the saturator temperature.

Saturator

The saturator is a high efficiency heat exchanger used to cool the gas from the presaturator down to the saturator temperature. While cooling, excess humidity will condense in the saturator and will drain as liquid water back to the presaturator. The gas, as it exits the saturator, is fully saturated with water vapor at the saturator temperature. This known saturation condition forms the foundation of an accurate two-pressure or hybrid two-pressure two-temperature humidity generation system.

Chamber

The test chamber has a removable lid. Gas flows into the chamber through a ¾" BSP straight thread female fitting located in the center wall. Chamber exhaust is though a ¾" BSP straight thread female fitting on the opposite wall.

Pressure Transducers

The saturator pressure transducers are very high accuracy quartz crystal oscillators that vary frequency with pressure. They transmit their readings to the G9-MCB via a serial (RS-232 or RS-485) connection.

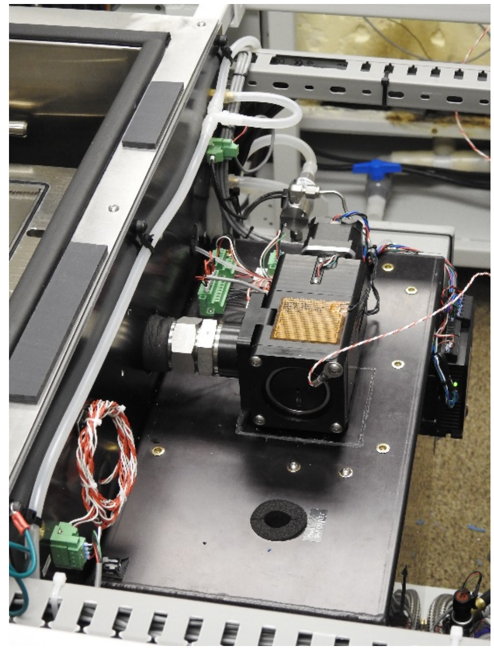
Pressure Sensor Heating

In order to prevent condensation in the pressure transducers, they are maintained at a fixed elevated temperature of approximately 90°C to ensure that they are always higher in temperature than the dew point of the gas they are measuring. If they were colder than the dew point of the measured gas, then condensation could occur within the sensors causing faulty readings. To maintain these sensors at this elevated 90°C temperature, they are mounted inside a thermally insulated, heated box. The internal temperature of the heated pressure box is maintained by an integral panel-mounted temperature controller.

Sharing of the Low Range Pressure Transducer

The pressure box also contains two solenoid valves used to select whether the low range sensor, *Pl*, measures saturator pressure or chamber pressure. When the saturator pressure is high (i.e., relative humidity is low), saturator pressure is measured by the high range pressure sensor while the low range pressure sensor measures only chamber pressure. When saturator pressure is low (i.e., relative humidity is high), the low range pressure sensor shares its measurement time between the saturator and chamber pressure. This sharing arrangement of the low range transducer significantly enhances humidity accuracy of the system when operating at high relative humidity.

Pressure Control System



The expansion valve is used to control the pressure of the gas flowing through the saturators. Like the flow control valve, the expansion valve is also a specially designed stepper-motor-drive GOP valve. Saturator pressures near ambient to full scale are controlled by this expansion valve. To control pressure, the rotation position of the plug is set by the stepper motor, under control of the embedded controller board, using feedback from the saturator pressure transducers, *Ph* and *Pl*.

Pneumatic Safety

The G9 is equipped with over-pressure relief valves at the air inlet, saturator, low pressure sensor, and chamber. In addition, pre-programmed software limits also protect the system against unexpected over-pressure conditions. If a software pressure limit is exceeded, the system will automatically shut down with error codes.

Fluid System

The fluid system is used to control the temperature of the chamber and various other system components. There are several separate fluid systems in the G9:

- Fluid Bath Circulation System
- Saturator Circulation System
- Bath Temperature Control
- Saturator Temperature Control
- Bath Liquid Level System
- Presaturator Liquid Level System
- Distilled Water Supply

Bath Fluid Circulation System

The Fluid Bath is a circulated water medium used to control the temperature of the chamber and saturator. Controlling the temperature of the bath fluid ultimately controls the temperature and stability of the chamber. The bath fluid circuit consists of several significant components; fluid pump, heater, refrigeration evaporator, saturator, fluid tank, optical liquid level sensors, and supply pump.

Water is circulated from the fluid pump, passing then through the fluid heater, being heated as necessary. After the heater, the path splits.

One path flows into the bath through the two inlet jets located near the top at opposite corners. Flowing in a circular motion around the outside of the chamber, the bath fluid temperature is measured by the fluid bath temperature probe mounted directly through the bath side wall. After passing over the temperature probe, it then exits through the bottom center of the bath.

The alternate path flows through the saturator. Water exiting the saturator then recombines with water exiting the bottom of the bath. The combined, remixed water then flows through the refrigeration evaporator where it is cooled as necessary. From the refrigeration evaporator, the water re-enters the pump and starts its round-trip journey again.

Saturator Circulation System

In a two-pressure G9 system, the saturator and bath circulation systems are coupled, maintain them at the same effective temperature. On a hybrid two-pressure two-temperature G9 system, the saturator and bath fluid circuits are independent of each other allowing for fully independent control of saturation and chamber temperatures.

Bath Temperature Control

Bath temperature is measured with a 100 ohm platinum resistance thermometer (PRT) connected to the RHS-T16 temperature measurement system. Bath cooling in accomplished though pulse-width-modulated (PWM) refrigerant injection into a fluid heat exchanger, controlled by the G9-GCB using a Proportional-Integral-Derivative (PID) algorithm. The bath is warmed by a pass-through immersion heater placed in series with the bath fluid pump. Heating is accomplished through PWM output to the heater, controlled by the G9-GCB using a PID algorithm.

Saturator Temperature Control

G9 systems of two-pressure design combine the saturator shares the bath fluid system. The saturator temperature will closely follow the bath temperature.

Hybrid G9 systems, of two-pressure two-temperature design, have a separate saturator temperature control. Saturator cooling is accomplished though PWM refrigerant injection into a fluid heat exchanger, controlled by the G9-GCB using a PID algorithm. The saturator is warmed by an immersion heater placed within the saturator fluid circuit. Heating is accomplished through PWM output to the heater, controlled by the G9-GCB using a PID algorithm.

Saturator fluid temperature is measured by a 100 ohm PRT connected to the RHS-T16 temperature measurement system.

Bath Liquid Level System

The Bath Liquid Level System maintains the level of the fluid bath at one of two separate levels. The lower level is slightly below the chamber lid, enabling the system to run and circulate water while the chamber lid is off. The lower level is useful for gaining access to the contents of the chamber while maintaining temperature control of the system.

The upper level is several centimeters above the chamber lid, requiring that the lid be in place. The upper level is the normal operating level of the system when generating humidity in the chamber. While at this upper level, the chamber is completely surrounded on all 6 sides by temperature controlled, circulated water.

Raising the bath is accomplished by actuating a fill solenoid. The fill solenoid is connected to the regulated air supply. When the solenoid actuates, air is pumped into the inverted water holding tank inside the bath and mounted directly beneath the chamber. This displaces the holding tank water into the bath, raising the water level of the bath.

Lowering the bath is accomplished by actuating a drain solenoid that allows the trapped air to escape from the holding tank. This allows water to once again occupy the space, lowering the bath water level.

The bath water level is determined by capacitive liquid level sensors; one at the upper control level and one at the lower control level. The water is raised and lowered as needed to maintain the level at the appropriate sensor position.

Water in the holding tank is maintained at a minimum operating level, ensuring that there is enough water to fill the bath and maintain an upper bath level. The level of the holding tank is sensed by an optical liquid level sensor. When the water level drops below this level sensor, water is automatically injected into the holding tank from the external distilled water supply tank by a small centrifugal pump.

Presaturator Liquid level System

The presaturator liquid level system maintains the water level within the presaturator. This is done utilizing a capacitive liquid level sensor and a high pressure pump that moves distilled water from the external distilled water supply tank into the presaturator. Since the high pressure pump can fill the presaturator while the system is running, the system can operate for extended periods without the need to shut it down. The only requirement is that the operator maintains enough distilled water in the external distilled water supply tank.

Distilled Water Supply

The distilled water supply tank is an external, non-pressurized, water storage container of approximately 80 liter capacity. The operator is responsible for maintaining water in this tank, filling it when required. Since water use by the system is rather slow, the water supply in this tank should generally last at least a week or more before needing to be refilled. Refilling may be done at any time, even while the system is running. To prevent damage to the system water pumps, it is recommended that the distilled water supply never be allowed to run completely dry. The distilled water supply tank should always have a minimum level of at least a few centimeters of water in the tank. It is the responsibility of the operator to ensure that there is sufficient water in this supply tank.

Thermal Safety

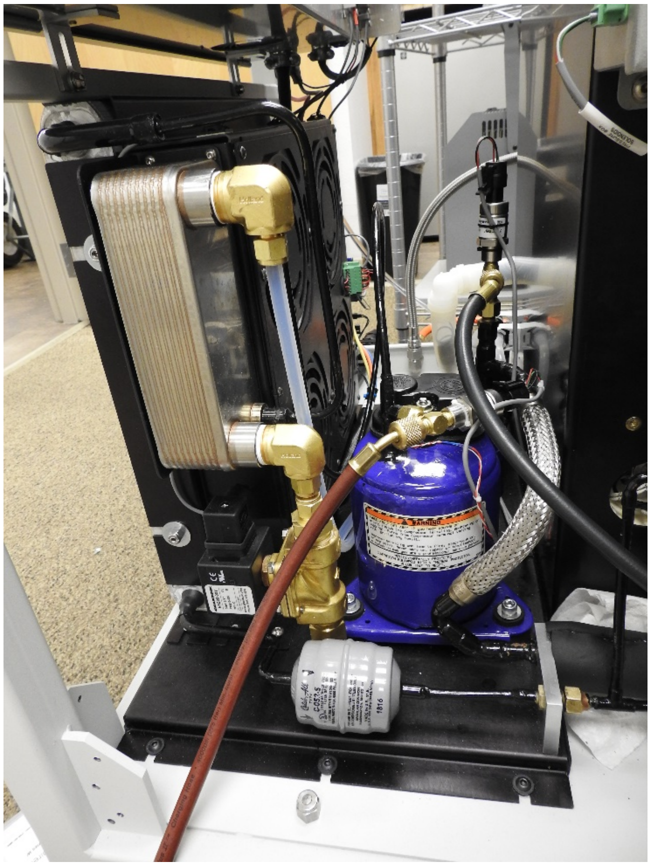
The bath and saturator temperatures are protected against accidental overheat through thermal cut-out switches. In addition, pre-programmed software limits will cause the system to automatically shut down, with error codes, if temperature limits are exceeded.

Bath Level Overflow Safety

The bath liquid level system is protected against overflow via the liquid level control system. Further mechanical protection is provided via an overflow drain hole near the top of the bath tank. This overflow ensures that water will drain back into the holding tank if it somehow reaches the overflow level.

Refrigeration System

The refrigeration system is a hermetically sealed, variable speed, closed-loop system used to cool the Fluid Bath and saturator. The refrigeration system utilizes .75 kg of R134A refrigerant.



Refrigerant is compressed into a heat-laden high pressure gas by the R134A Compressor. The high pressure hot gas is passed first through the water cooled condenser then through the air-cooled condenser. Whether the hot high-pressure refrigerant is cooled in the water-cooled condenser or the air-cooled condenser, the refrigerant cools and condenses to a high pressure liquid. The high pressure liquid accumulates in the receiver tank. It passes then through the filter/dryer and is metered into the evaporator via the cooling control solenoid, absorbing heat (cooling) as it expands to a low pressure gas. The low pressure, heat-laden gas is then returned to the suction side of the R134A compressor where the process repeats itself.

The bath injection solenoid is controlled by the embedded computer using pulse width modulation based on the measured bath temperature. The saturator injection solenoid is controlled by the embedded computer using pulse width modulation based on the measured saturator temperature.

The refrigerant system is expected to operate over a very wide temperature range (about 5 to 90°C) and over a wide variation of load conditions (almost no-load while maintaining temperature at a fixed point, to full-load while cooling from high-to-low temperature). During times of high cooling demand, the compressor speed is ramped up to handle the increased demand. During times of low demand, such as maintaining an established temperature, the compressor runs at a low speed (often an idle speed). This lessens both the power requirements and the wear on the refrigeration system.

Compressor

The R134A compressor is a hermetic refrigeration compressor that is capable of pulling to low pressures on the input side, and high pressures on the discharge side. These two pressures are measured by the pressure sensors *Prl* and *Prh*.

During times of normal cooling demand, the compressor runs continuously but at a speed varied by the demand. However, when there is no cooling demand for a period of time, such as when the system is heating to a warmer temperature, the compressor is turned off.

Condensers

There are two condensers (also called heat exchangers) in the system, connected in series. The first condenser is water-cooled, followed by an air-cooled condenser. The amount of cooling water that flows through the water-cooled condenser is adjustable via a manual valve. When the compressor is on, a cooling water solenoid valve opens, allowing water to flow through the condenser. When the compressor is off, the cooling water solenoid valve shuts off, stopping the flow of cooling water to the condenser. The cooling water is expected to be from a pressurized source, such as normal tap water, at or near room temperature. The discharge water should be connected to a waste water drain such as a floor drain or sink. Alternatively, cooling water may be supplied from a recirculating water chiller. The chiller must be equipped with a recirculating pump. Desired temperature output from the water chiller should be approximately 10 to 30°C.

Under normal conditions, when there is sufficient cooling water to properly cool and condense the compressor's refrigerant gas discharge to room temperature or lower, the air-cooled condenser is simply receiving room temperature condensed refrigerant from the water cooled condenser. In this case the air-cooled condenser does nothing, and no heat is dumped into the room. If, however, there is no cooling water, or the use of cooling water is disabled in the software, the water-cooled condenser fails to properly cool and condense the refrigerant gas. It is then the job of the air-cooled condenser to cool the gas to room temperature. The higher the G9 heat demand (such as those times that the system is cooling to a lower setpoint), the more heat will be dumped into the room through this air-cooled condenser.

If cooling water is not utilized, it is preferred if the facility air conditioning is able to handle the added heat load of the G9. Peak heat load of the G9 is estimated at approximately 2.5 kW.

Controlled Injection Valve(s)

The bath temperature is maintained by heating or cooling as needed. Cooling is accomplished by refrigerant injection through the controlled injection valve. This is a solenoid valve, actuated by a 24VDC pulse width modulated signal. When energized, the valve opens allowing refrigerant to be injected into the evaporator, causing it to cool the bath fluid. The pulse width of the valve directly controls the amount of refrigerant injected, thereby affecting the temperature of the bath fluid. The valve is generally pulsed at a fixed interval with varying pulse width.

On a hybrid G9 system equipped with two-pressure two-temperature capability, a second refrigeration injection valve is used to cool the saturator independently of the bath.

Evaporator(s)

The refrigeration evaporator is a brazed plate heat exchanger thermally coupling the bath fluid with the R134A refrigerant system. One side of the evaporator is connected to the refrigeration system, while the bath fluid flows through the other side. As liquid refrigerant is injected into the evaporator, it expands into gas. This expansion causes cooling (by absorbing heat), which lowers the temperature of the bath fluid that is flowing through the other side.

On a hybrid G9 system equipped with two-pressure two-temperature capability, a second refrigeration evaporator is used to cool the saturator independently of the bath.

Refrigeration Safety

The refrigeration system is protected against thermal overload through a thermal cut-out switch located on the compressor.

Electrical System

200-230 VAC power enters the system via the power connector located at the back panel. The power then enters the electrical power distribution box, located behind the side panel, and then connects to the system's two-pole main circuit breaker. When the breaker is turned on, power is also applied to the input of the 5 VDC power supply.

Power from the 5 VDC power supply is applied to the back panel power switch. This is considered the system's main on/off switch for daily use. When off, no AC or DC power is applied to any other part of the G9 system. When the back panel power switch is turned on, however, 5 VDC is then applied to the control inputs of two solid-state relays. These relays are connected between the output of the main power circuit breakers previously discussed, and the AC power input to the rest of the system. Therefore, if the main power circuit breaker is turned on, but the power switch at the back panel is off, AC power travels through the main circuit breaker, but stops at the input of these two DC-controlled solid-state main-power relays. When the power switch is on, these two DC-controlled solid-state main-power relays also turn on, allowing AC power to reach other parts of the system, including the 24 VDC power supply, through their individual circuit breaker switches.   The 24 VDC power supply provides power to activate solenoids, pumps, fans, and the electronics.

Power Panel

220 VAC nominal power, supplied from the user's facility, enters the Model G9 at the AC receptacle at the back panel. From there it proceeds to the Power Panel. Inside the power panel are two lines of DIN rail mounted. A two-pole 30A molded case circuit breaker (UL489) protects the unit. Two DC power supplies housed within the power panel convert the 220 VAC to 5 VDC used for operating the back panel power switch, and a 24 VDC power supply used for supplying all solenoid valves, stepper motors, pumps, and the controller board. 220VAC, 5 VDC and 24VDC voltages are present inside the Power Panel.

5 VDC powers the back panel power switch only.

24 VDC powers the Controller Board and several devices external to the Panel such as the electronics, solenoids, pumps, and fans.

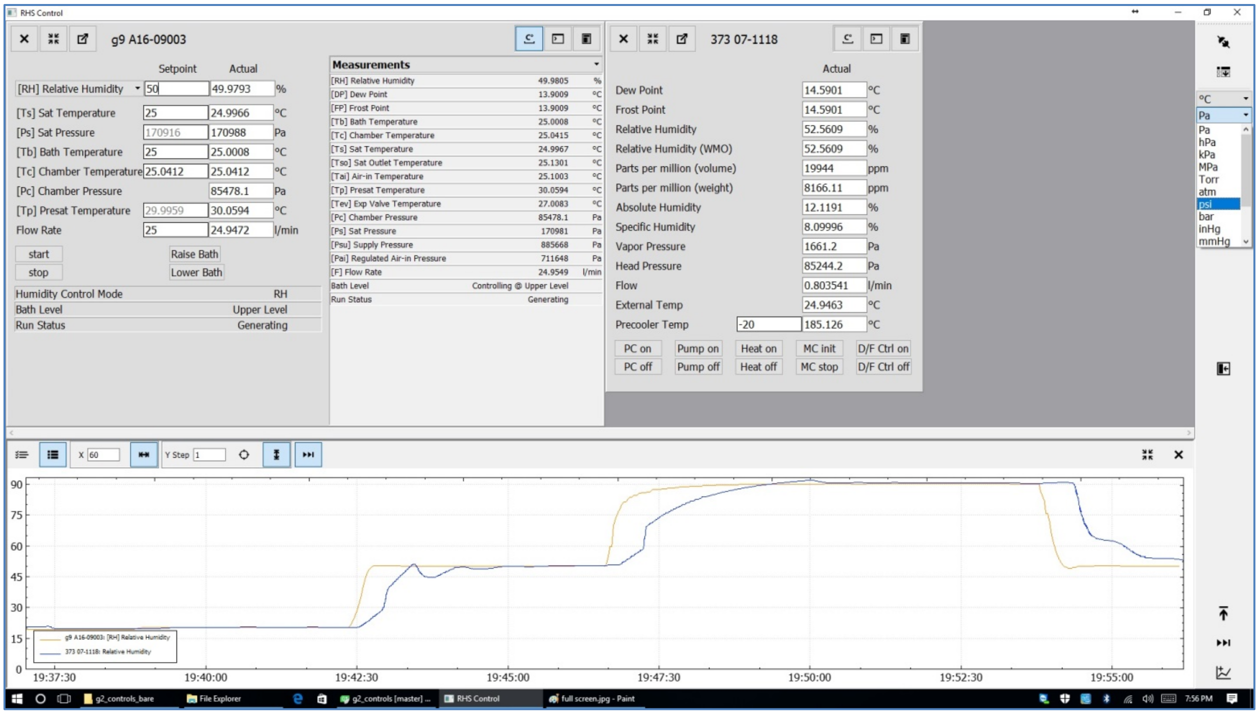
The 220 VAC leaves the Power Panel and goes to several devices external to the Panel such heaters, water pump, the heated pressure sensor box, and a 48 VDC power supply which operates the refrigeration system. All AC outputs from the power panel are appropriately protected with din rail mounted circuit breakers within the power panel.

Electrical Safety

All high voltage electrical circuits are protected with current-overload breakers. In addition, high voltage breakers, switches, and interconnects are within voltage-rated enclosures. With the exception of high power components such as pumps, heaters, and the refrigeration compressor power supply, all other devices are operated at a voltage of 24 VDC or less. The system chassis is metal, grounded directly to earth via the GND connection of the incoming AC power cable.

User Interface

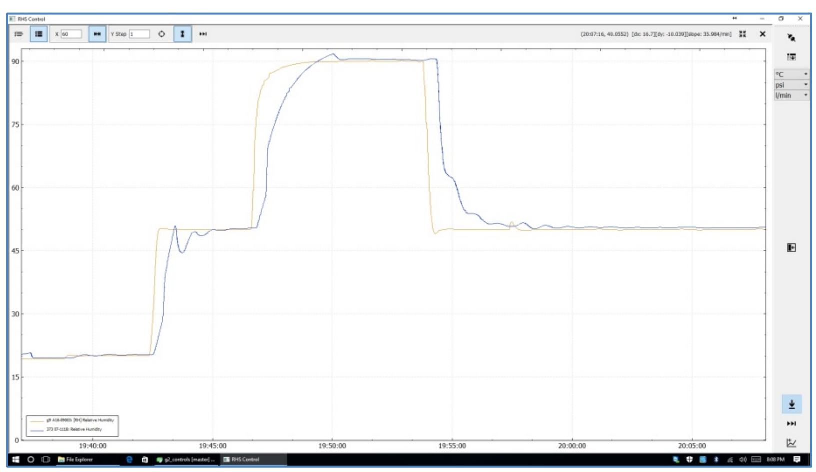
The User Interface is a desktop PC running Windows™ 10 (or later version), and our custom *RHS Control* software. The RHS Control program communicates with the G9 Embedded Control Board via a serial communication port. Through the RHS Control program, temperature, pressure, mass flow, and control parameters, such as humidity, are made available to the user in real time. The RHS Control



software may be operated traditionally using a keyboard and mouse, but is also optimized for use with a touch screen. For example, the graph window may be easily manipulated using multi-touch for pinch-and-zoom capability.

Fully Automated Operation

While the embedded G9-GCB controller performs all system control functions on a second-to-second basis, a PC running the RHSA Control software complements this by allowing user interaction with the system. Working in conjunction with one another, RHS Control and the G9-GCB provide for fully automated operation of the G9 humidity generator together with data visualization and storage.

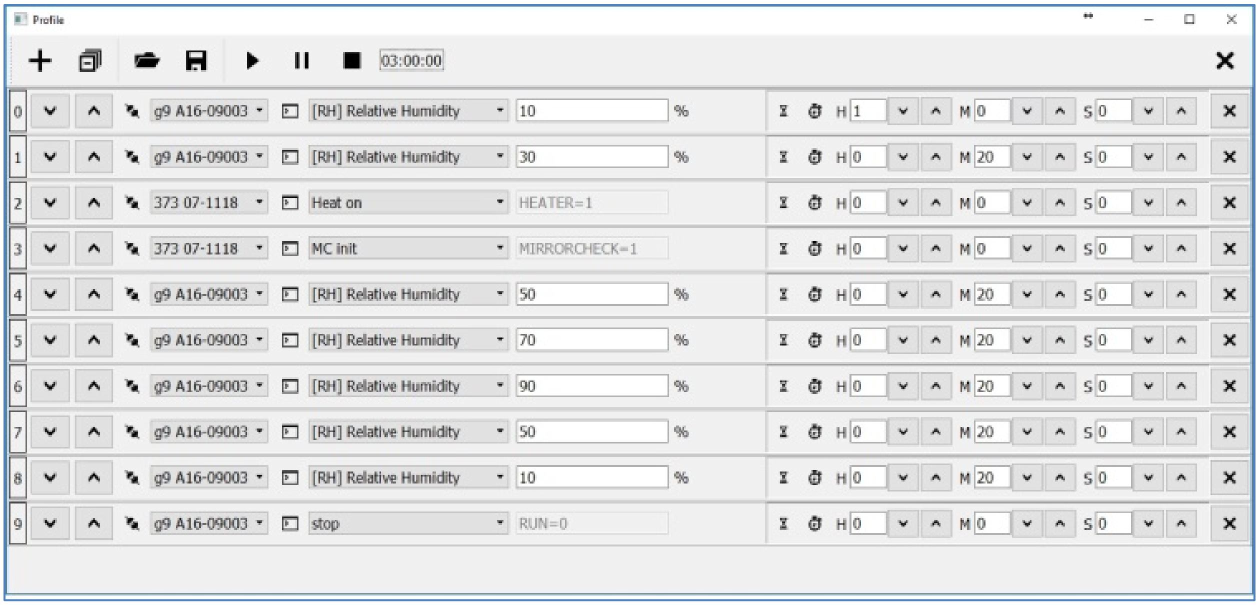


Numeric / Graphing Display

Utilizing the supplied RHS Control software, all parameters are available for display in a numeric format, or for graphical display on an auto-updating line chart. All collected data is automatically stored to disk on the PC.

Auto Profiling

In addition to direct, real-time, user setpoint input, an auto-profile can be prepared on screen giving the system a set of future, time-based, setpoint instructions. With auto-profiling, an entire series of setpoints with associated run times is pre-programmed on screen for subsequent execution of the sequence. Or it may be stored to disk for later retrieval and execution. Auto-profiling allows the system to run full sequences of humidity/temperature/flow points completely unattended, storing system and instrument



data the entire time. In addition, if other instruments are also connected to RHS Control (such as RHS/MBW Chilled Mirror Hygrometers), they too may be sent commands as part of the auto-profile sequence. In this way, any available connected instrument may be included to accept commands from auto-profiling. A perfect example of this is the ability of the auto-profile to command a 373 Chilled Mirror to enable its heater , setting it to a fixed or delta temperature, prior to commanding the G9 to run high dew point values.

Connection to Chilled Mirrors and Other Instruments

RHS Control already recognizes all RH Systems and MBW brand instruments. Simply connect one of these instruments and its associated data will immediately be retrieved, displayed and stored to disk. All data files have a common data storage interval and common time stamps and tab delimiting, ready for direct import into Excel or other data analysis packages. Data files are stored as straight text in a tab delimited format with common time intervals and common time stamps, ready for direct import to Excel or other data analysis programs.

7. System Specifications

Relative Humidity Range.. 5 to 99%*
Relative Humidity Resolution: ....0.01% RH
Relative Humidity Accuracy: .... <±0.3% RH**
Frost Point Temperature Range: ....-25 to 0 °C
Dew Point Temperature Range:...-28 to 70 °C***
Frost/Dew Point Accuracy:... ±0.05 °C***
Bath Temperature Range: .... 0 to 85 °C
Bath Temperature Control Stability:.. ±0.02 °C
Bath Temperature Uniformity: .... 0.04 °C
Bath Temperature Heating/Cooling Rate: .... ~2 minutes per °C
Temperature Measurement Accuracy:... ±0.025 °C
Gas Type:...Air or Nitrogen
Gas Flow Rate Range: ....5 to 150 slpm
Gas Flow Rate Resolution: ....0.1 slpm
Gas Flow Rate Accuracy: ....±3 slpm
Test Chamber Dimensions:..300 mm x 300 mm x 300 mm
Physical Dimensions:..0.8 m x 1.2 m x 0.9 m
Gas Pressure Rating (MAWP):...200 psig
Saturation Pressure – Low Range:.. 23 psia
Saturation Pressure Accuracy – Low Range:..±0.0023 psia
Saturation Pressure Display Resolution – Low Range: .... 0.001 psia
Saturation Pressure – High Range: .... 200 psia
Saturation Pressure Accuracy – High Range:... ±0.02 psia
Saturation Pressure Display Resolution – High Range: .... 0.01 psia
Test Chamber Pressure Range: ....Ambient
Test Chamber Pressure Accuracy:..±0.0023 psia
Test Chamber Pressure Resolution: .... 0.001 psia

Utility Requirements

Electrical Power:... 200-240 VAC, 30 A, 1-phase, 50-60 Hz
Gas Supply:.................................. maximum 200 psig @ 7 scfm (1.7 MPa @ 100 slpm)
Cooling Water (optional):..........................approximately 3 gpm (12 L/min) @ 20-25°C

Environmental

Operating Temperature:.. 15 to 40°C
Storage Temperature:.. 0 to 50°C
Humidity: ....10 to 95% non-condensing

*5 to 99% for bath temp 5 to 70 °C. Maximum specified RH is 85% at 85°C (approx. 82°C DP).
** RH accuracy is not specified above 70°C bath temp.
*** Dew point accuracy is not specified above 70 °C.

8. References:

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[3] R. Hardy, “ITS-90 formulations for vapor pressure, frostpoint temperature, dewpoint temperature, and enhancement factors in the range –100 to +100 C,” *Papers and Abstracts of the Third International Symposium on Humidity and Moisture*, vol. 1, National Physical Laboratory, Teddington, UK, pp. 214–222, April 1998.