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MASTER'S DEGREE THESIS

TESI DI LAUREA MAGISTRALE

Experimental characterization and validation of the individual uncertainty components to improve the humidity calibration of a two pressure humidity generator

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INDEX

LIST OF FIGURES

LIST OF TABLES

List of Equations

1. Introduction

Numerous physical, chemical, and biological processes are affected by the presence of water vapor in air or other carrier gases. Many industries value the need humidity measures and its accuracy as the amount of water vapour plays a crucial role in terms of business costs, product quality, health, and safety.

Differently from many others physical quantities, it is challenging to perform humidity measurements with a high accuracy. For instance, it is possible to determine the mass of an object by weighing it

in a normal laboratory to an accuracy of one part in 100000.

It is similar to the air pressures that can frequently only be measured to three parts per hundred, there is uncertainty in the outcome of ± 3%.

It is vital to employ the proper measuring technique in order to obtain a reliable humidity measurement, together with a rigorous evaluation of the associated uncertainties. Therefore, it is necessary to define the humidity quantity to be directly measured such as Relative Humidity, Dewpoint Temperature, Frost Point temperature, molar fraction, etc by choosing the appropriate measuring method. The device must be carefully calibrated against a reference standard.

1.1 Metrology and Its Importance

The International Bureau of Weight and Measures states that: “Metrology is the science of measurement, embracing both experimental and theoretical determinations at any level of uncertainty in any field of science and technology." It is surely at the core of all practical scientific endeavours. Metrology is important because almost all of everyday life, not to mention practical science, technology, engineering and medicine, involves measurements that we rely on for our health, commercial prosperity, quality of life and the protection of the environment. Metrology is the structure that ensures these measurements are stable, comparable and accurate, providing confidence in measurement at a stated level (usually by quoting a measurement uncertainty). Measurement qualities and uncertainties which are associated with a measurement reduces waste, allows trade, enables infrastructure to function, technology to advance, the economy to prosper, encourage global agreement, collaboration, and trade, and ensure the ongoing health and safety, and quality of life. [1]

The field of metrology is quite significant. Its success and durability are demonstrated by the fact that it frequently passes unnoticed. It runs the risk of being undervalued and underappreciated as a result. As the world struggles to recover from the COVID-19 epidemic, restore global economies, and refocus on tackling global great issues and utilizing emerging technology, the stability that metrology gives to the quality infrastructure will be particularly crucial.

For research and society to advance sustainably, accurate measurements are more important than ever. Providing reliable definitions of measuring units and the realization of main standards for these, ensuring the traceability to the SI units, metrology stands at the top of this quality infrastructure. It also improves these realizations to continue to reduce uncertainties for the end user.

The metrology activity is coordinated by national laboratories, such as the National Institute of Standards and Technology (NIST, USA) and the National Institute of Metrology, Quality and Technology (Inmetro, Brazil), which are internationally coordinated by the BIPM. In parallel, standardization is coordinated by the International Organization for Standardization (ISO), together with other organizations like the Versailles Project on Advanced Materials and Standards (VAMAS), whose main objective is to support trade in high-technology products, through international collaborative projects aimed at providing the technical basis for drafting codes of practice and specifications for advanced materials. INRiM (Istituto nazionale di ricerca metrologica) is one key research organization that continuously focuses on specific metrological research and development activities. [2]

1.2 A Brief Overview On INRiM

The National Institute of Metrological Research (INRiM) is a national public body established by Legislative Decree no. Of 21 January 2004. In order to fulfill its obligations as the primary metrological institute under Law No. 273, INRiM conducts and supports research in the field of metrology, develops the most cutting-edge standards, measurement techniques, and related technologies. The high scientific-technological contents specific to metrological research. [3]

To this end, INRiM creates and maintains national standards for the realization of SI and in order to provide the legal value of the measures in the sectors of industry, trade, scientific research, the protection of health and the environment. In order to enhance national technological growth and increase citizen quality of life and services, INRiM also improves and disseminates knowledge and findings in the science of measurements and material research.

The National Institute for Metrological Research (INRIM) focuses on studying metrology (measuring sciences), performing material research, and creating cutting-edge technologies and apparatuses. The nanofabrication laboratory Nano facility Piemonte provides an infrastructure for the manipulation of new types of nano-objects by nanolithography and for the development of novel structures for high-density magnetic recording and sensing. INRIM has published significant results studying nanotechnologies, metrology for biosciences, chemistry, and the environment.

2. Scope of Investigation

The scope of the experiment is to characterize the relative humidity generator to obtain and analyze the quantities associated with the relative humidity such as Dew point temperatures, Frost point temperatures, Uniformity in chamber temperatures and evaluating the uncertainty parameters.

2.1 Definitions Related to Humidity

2.1.1 What Is Humidity?

Water vapor can be found in air or other gases, and this is referred to as humidity. Water vapor is the gaseous form of water and is conceptualized similarly to other types of gases. The air around us contains roughly one hundredth (or one percent) of it, and it is typically translucent.

Changes in humidity level are due to the evaporation of water (or sublimation of ice) and the condensation (or sublimation) of water vapor, whose rate is strongly dependent on the air or water temperature. Air (or empty space or any other gas) has a given capacity to absorb water vapor whose capacity depends mainly on temperature. Generally, the hotter the air, the more water vapor it can hold before reaching saturation. [4]

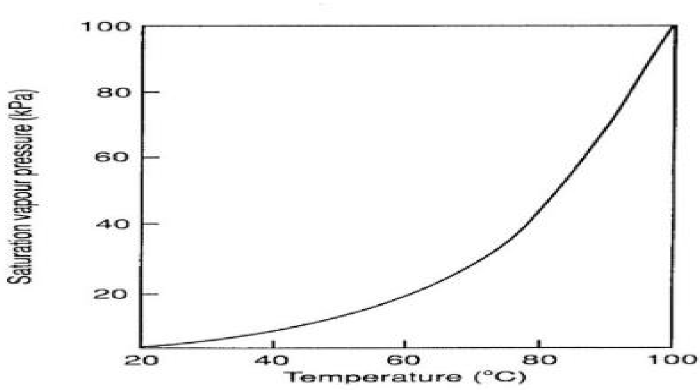


FIGURE 1 - GRAPH ILLUSTRATING THAT THE SATURATION VAPOUR PRESSURE OF WATER INCREASES WITH TEMPERATURE BASED ON THE CLAUSIUS-CLAPEYRON EQUATION

The term "saturated air" refers to air that has reached its maximum water vapor capacity at a given temperature. The air's relative humidity reflects how completely saturated it is with water vapor. The actual amount of water vapour is expressed using a variety of additional (Absolute) measurements. [5]

Since it has been recognized that humidity significantly affects quality of life, product quality, safety, cost, and health, humidity measurements have become crucial, particularly in industrialized nations. Applications for measuring humidity have significantly increased as a result, and research and development initiatives to enhance humidity measurement methodologies, accuracy, and instrumentation dependability have also increased. [4]

2.1.2 Temperature

Temperature is the degree to which a body or environment is hot or cold. Specifically, it is a measurement of the of the particle's average kinetic energy of the molecules, which is a sort of energy connected to the random motion of the molecules themselves.

When one body comes into contact with another that is colder or hotter, heat is produced as a result of thermal energy, which is a form of energy that exists in all matter. A thermometer is used to measure temperature, which is calibrated using a variety of temperature scales that historically defined various thermometric substances and reference points. The three most common scales are the Celsius scale (formerly known as centigrade, marked as °C), the Fahrenheit scale (denoted as °F), and the Kelvin scale (denoted as K), with the latter being mostly utilized for scientific purposes and being defined as the temperature unit of the International System of Units (SI).

Absolute zero is the lowest possible temperature, at which a body can no longer lose thermal energy. The third law of thermodynamics acknowledges that it cannot be reached experimentally and can only be approached extremely roughly (100 pK).

The temperature has a considerable impact on humidity. If this isn't considered, there could be mistakes so significant that the measurement becomes useless. The temperature inhomogeneity in a process, room, or chamber is frequently the contribution to uncertainty in humidity measurement. [4]

- Temperature dependence exists for all hygrometers. The effects might be minimal in some instruments, but this isn't always the case. The impact of temperature is greatest in devices that use an electrical sensor.
- Another unwanted effect of temperature is condensation It frequently contributes to humidity measurement errors. It can happen in colder areas where the temperature is below the dew point temperature of the gas. The sample systems should always be heated if necessary to maintain them at a temperature above maximum dew point in order to avoid condensation.
- Temperature has a significant impact on the saturation vapour pressure of water, that in turn influences other humidity quantities as the relative humidity. Every 10 degrees Celsius increase in temperature doubles the air's ability to hold water vapor in the atmosphere. Over the course of the temperature change, the steepness of this variation steadily changes.
- Many materials, especially the organic ones, salts, and anything with pores, include moisture as a structural component. The amount of water in this substance is influenced by temperature, the humidity of the surrounding gas, and other factors. Water moves from the substance to the surrounding gas and vice versa as the temperature changes.

2.1.3 Pressure

The force delivered perpendicularly to an object's surface per unit area across which that force is dispersed is known as pressure (symbol: p). Pressure is expressed by using a variety of units. One Newton per square meter $\frac{N}{m^2}$ defined as the pascal (Pa). It is the SI unit of pressure. Additionally, the standard unit of pressure in the imperial and American customary systems is the pound-force per square inch (psi).

The atmosphere(atm) is another SI unit of pressure. It is defined as the sea level pressure of a standard atmosphere (equal to 101325 Pa or equivalently 1013.25 millibars

To indicate pressures in terms of the height of a certain fluid's column in a manometer, manometric units such as the centimeter of water, millimeter of mercury, and inch of mercury are employed. The variation in the overall pressure of the gas system may have an effect on measured humidity.

In a gas mixture such as room air, the total pressure P_{total} of the system can be represented as the sum of partial pressures.

$$P_{total} = P_{nitrogen} + P_{oxygen} + P_{water} + P_{others}$$

EQUATION 1 - TOTAL PRESSURE

Hence, if any partial pressure of the component varies, the total pressure will vary. Also, if the total system pressure is changed either by compression or expansion, each of the component partial pressures will be changed proportionally.

2.2 Definitions Related to Calibration

2.2.1 Traceability

Metrology is vital to business and industry, not just from the perspective of the consumer but also from that of those working in manufacturing. Both parties must have faith in the measurements they rely on. It is crucial that measuring devices are routinely calibrated against more precise standards during the production process, and that their calibration may finally be traced to even more precise national measurement standards at both the national and international levels. A chain of traceable calibrations is established once these multiple levels of calibration have been documented. [4]

Traceability is the ability to link a measurement's outcome to a regional, national, or even global measurement standard and to document this connection. A measurement standard that is also traceable must be used to calibrate the measuring device. Thus, the capacity to be related to stated references, typically national or international, through an unbroken chain of comparisons, each with acknowledged uncertainties, is what is meant by the term "traceability" for a measurement result or standard value. The idea of traceability is crucial because it enables comparisons of measurement accuracy across the globe using a uniform method for calculating measurement uncertainty.

As depicted in the picture, the measurement accuracy is lost at each point in such a chain of traceability. As a result, the standards with the highest accuracy are the international standards, while the standards, while the lowest level will have been defined. It will be acceptable or suitable to use that standard with this reduced accuracy. [6]

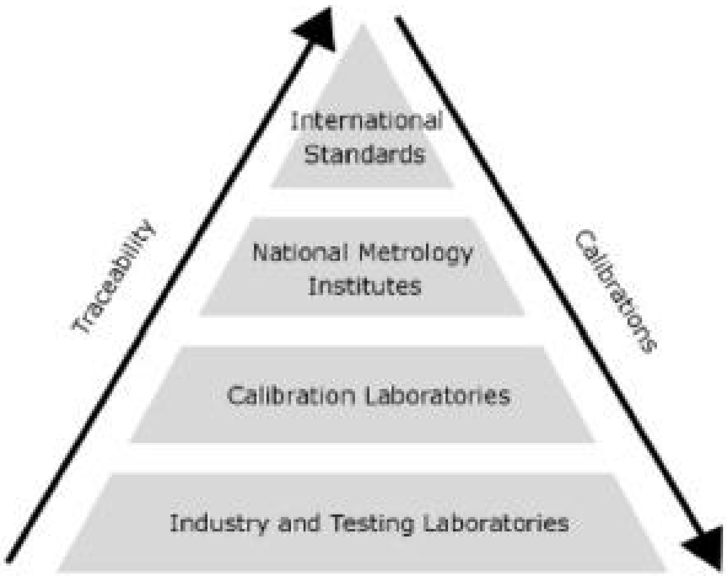


FIGURE 2 - MEASUREMENT TRACEABILITY PYRAMID

2.2.2 Standards

The term "standard" has two distinct meanings in measurement science: first, it refers to a commonly accepted specification, technical guideline, or other comparable document; second, it refers to a measurement standard. This note focuses on measurement standards, which might be a physical measure, measuring instrument, reference item, or measuring system designed to define, realize, preserve, or replicate a unit or one or more values of a quantity to serve as a reference. For instance, a cylindrical piece of metal weighing one kilogram, which symbolizes the international standard, gives the amount "mass" its physical shape, and gauge blocks stand in for specific values of the quantity "length."

A reference standard is a device, typically having the best metrological quality obtainable at that location or in that organization. It is used by calibration laboratories in order to calibrate their working standards.

2.2.3 Uncertainty

In its broadest definition, "uncertainty of measurement" refers to uncertainty regarding the accuracy of measurement.

Formally, "uncertainty of measurement" is a parameter that describes the dispersion of values that can be properly assigned to the measurand and is connected with a measurement's outcome. [4]

- Standard uncertainty (u) refers to the uncertainty of the result of a measurement that can be evaluated by means of two different approaches: .

1. Type A evaluation (of uncertainty) is a method of evaluation of uncertainty on the statistical analysis of series of observations. (e.g., the standard deviation).
2. Type B evaluation (of uncertainty) is a method of evaluation of uncertainty by means other than the statistical analysis of series of observations.

- The term "combined standard uncertainty" (u_c)refers to the standard uncertainty of a measurement's result when that result is derived from the values of several other quantities, and it is equal to the positive square root of the sum of terms, which are the variances or covariances of those other quantities weighted in accordance with how changes in those quantities affect the measurement result.

- Expanded uncertainty (U)is a quantity that defines a range around a measurement's outcome that might be anticipated to include a significant portion of the distribution of values that could be legitimately assigned to the measurand.

2.2.4 Calibration

One of the key procedures for maintaining the accuracy of instrument is through instrument calibration. In order to to continuously get a measurement result that is within an acceptable range, an instrument must be calibrated. A core principle of instrumentation design is to eliminate or reduce factors that lead to faulty measurements.

The calibration process often entails using the instrument to test samples of one or more known values called "calibrators," however the precise process may vary depending on the device. The findings are utilized to establish a connection between the instrument's measurement method and the measured values. When samples of unknown values are examined while the product is being used normally, the instrument can then produce more accurate results.

To establish the correlation at particular places within the instrument's operational range, calibrations are carried out using just a few calibrators. Although it may be preferable to employ a large number of calibrators to create the calibration relationship, or "curve," the effort and time required to prepare and test a large number of calibrators may be more than the level of performance that is attained. A trade-off needs to be established between the desired degree of product performance and the work required to complete the calibration.

3. Two- Pressure Humidity Generator

3.1 Introduction

The NIST-developed "two pressure" humidity generator's basic idea is used by the Thunder Scientific 2500 Benchtop Humidity Generator, a self-contained device that can generate a humid gas will a well-known amount of water vapor. It's performance is also ensured by the continuous calibration, assessment, and verification of the internal instrumentation.

The control system of the humidity generator can be interfaced to an external PC by a bi-directional RS-232C serial port and a dedicated software owned by the Thunder Scientific (ControLog™). [7]

Humidity and temperature setpoint values are input by the operator from the front panel keypad. Visual indications of system status are displayed in real time on the Liquid Crystal Display. The automatic features of this system allow the 2500 to generate humidity and temperature setpoints completely unattended. This automated approach frees the operating technician from the task of system monitoring and adjustments, allowing him time to perform other vital tasks.

FIGURE 3 - THE MODEL 2500, A SELF- CONTAINED MOBILE TWO PRESSURE HUMIDITY- STANDARD GENERATOR.

3.2 History Of Two-Pressure Humidity Calibration

In the past, on-site verification was achieved either by carrying out a full laboratory calibration or utilizing a portable transfer device. However, employing a portable transfer device that is calibrated in the lab before being transported to the comparison location only offers the best comparison ratio of about 1:1. Full laboratory calibration utilizing humidity-generating equipment is more precise, but it requires removing the instrument to be calibrated from its installation, bringing it to the lab, and then restoring it after it is properly calibrated, which might result in a variety of measurement inaccuracies.

The National Bureau of Standards (now the National Institute of Standards and Technology NIST) worked to address these issues over time by creating the two-pressure humidity calibration technology that would eventually become the commercial product used today in the majority of labs around the world. E.R. Weaver and R. Riley created a device in 1948 that generated and controlled humidity using pressure rather than water vapor as the basis for the modern commercial device we use today. [8]

Wexler and Daniels employed temperature control to saturate a gas with water vapor at a specific temperature and then elevate it to a higher value, enabling the measurement of temperature and pressure to be used to calculate the relative humidity. Today's commercially available integrated two-pressure, two-temperature humidity generators provide independent control of temperature and pressure. Since the value of relative humidity is a mathematical connection dependent on pressure and temperature, NCSL International has designated this device as an intrinsic/derived standard.

3.3 Applications

Pharmaceutical, aerospace, and semiconductor sectors make extensive use of portable two-pressure humidity generating calibration equipment. Additionally, it's the most popular method employed by sensor makers. These pieces of equipment are used in "PMEL" laboratories run by the US Air Force, US Army, and US Navy to calibrate humidity sensors. Additionally, the technology is often used in medical laboratories, pharmaceutical production, semiconductor clean room monitoring sensors, and HVAC environmental controls. There are a ton of different applications.

Hygrometer calibration, certification, and humidity sensor original calibration are other fields in which portable two-pressure humidity generating calibration equipment is an invaluable resource. Additionally, this technique is essential for large-scale humidity sensor calibration manufacturing as well as for specialized long-term environmental exposure testing for weather-related calibration of air and land-based humidity sensor instrument packages. [8]

3.4 Principle Of Operation

The working principle of the 2500 humidity generator is based on the two-pressure technique

according to Dalton's Law of Partial Pressure, the pressure that a mixture of gases exerts in each volume at a certain temperature is equal to the total of the pressures that each individual gas would exert if it were the only gas occupying the volume at that temperature.

In the two-pressure technique, air or another carrier gas, such as nitrogen, is saturated with water vapor at a certain pressure and temperature. The saturated gas is then isothermally expanded to the test chamber, whose pressure is always equal to the environmental pressure through an expansion valve. The relative humidity at chamber pressure may therefore be roughly calculated as the ratio of two absolute pressures if the gas temperature is kept constant during expansion process.

$$\%RH = (P(Chamber) \div P(Saturator)) \times 100$$

EQUATION 2 - RELATIVE HUMIDITY AT CHAMBER PRESSURE

If the expansion process is not isothermal (this is the case of the Thunder 2500 where there is a slight difference between saturator and chamber temperature), the following formula is used to obtain a more precise value of the relative humidity of the humid gas in the test chamber [9]:

$$\%RH = \frac{f_w(P_s, T_s)}{f_w(P_c, T_c)} \cdot \frac{e_w(T_s)}{e_w(T_c)} \cdot \frac{P_C}{P_S} \cdot 100$$

EQUATION 3 - RELATIVE HUMIDITY IN TEST CHAMBER

Where,

f_w= Enhancement factor

e_w= Saturation Vapor Pressure

P_s= Saturation Pressure

P_c= Chamber Pressure

T_S= Saturation Temperature

T_C= Chamber Temperature

The enhancement factors are introduced in order to take account of the non-ideality of the water vapor (in first-order approximation they can be assumed equal to 1).So the Thunder 2500 can be assumed to work as a two-pressure, two-temperature humidity generator, where no humidity sensors (like psychrometers, dewpoint hygrometers, or solid-state sensors) are required to monitor the humidity produced because it takes advantage on the fundamental laws of temperature and pressure.

The two-pressure, two-temperature humidity generator is covered in a Recommended Practice for Intrinsic/Derived Standards (RISP-5) document from NCSL International. [8]

The measurement of the saturation and chamber pressure, as well as the saturation temperature, and the preservation of almost perfect isothermal conditions are the only factors that affect humidity generated in the test chamber. Accuracy of the pressure and temperature readings and temperature homogeneity throughout the Thunder 2500 are key factors in precision humidity generation.

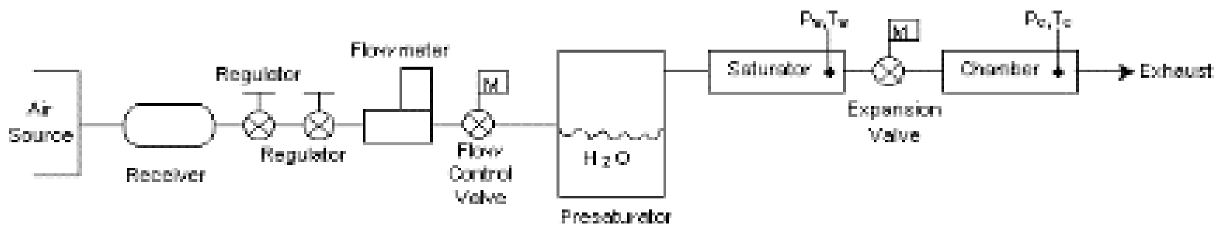


FIGURE 4 - THE MODEL 2500, A SELF- CONTAINED MOBILE TWO PRESSURE HUMIDITY- STANDARD GENERATOR

The humidity generator employs compressed air that is directed to a receiver at a maximum pressure of 175 psia (1207 kPa) from either a portable oil-free air compressor or another equivalent source.

The air is then sent to a flow control valve after passing through two regulators to provide a controlled pressure from a value slightly above the ambient one around 150 psia (1034 kPa).

Although flow rate has no effect on humidity, the flow control valve is configured to allow 2 to 20 slpm of air to pass through the system. A flowmeter put upstream of the flow control valve keeps track of the flow rate. The gas then travels through a pre-saturator. The pre-saturator is a vertical cylinder that holds water and is kept at a temperature that is 10 to 20 °C.

The air is warmed to "at or near" the pre-saturator temperature as it passes through it, becoming saturated with water vapor (RH = 100 %). Then the gas goes into saturator, a fluid-encapsulated heat exchanger kept at the required saturation temperature where it cools and its water vapor content decreases by condensation in order to reach a dew point temperature equal to the saturation temperature, so guaranteeing a relative humidity of exactly 100 %. The saturation pressure Ps and the saturation temperature Ts are monitored at the end of the saturator. [10]

The gas is then expanded to the pressure of the test chamber PC, by means of the expansion valve. The valve is heated to maintain the gas temperature above the dew point temperature, to prevent condensation as the gas naturally cools during an adiabatic expansion process.

The heated valve isn't fully able to offset the cooling effects of the expansion, so before entering the test chamber, the gas regains thermal equilibrium with the fluid surrounding the chamber and the saturator by passing through a small heat exchanger. Inside the test chamber, the gas pressure Pc and gas temperature Tc are monitored, where Pc is close to the ambient pressure since the humid gas directly exhausts to the external environment.

A flowing water/glycol mixture that surrounds both the saturator and the test chamber allows to the regulation of the saturation and the chamber temperature at a constant value between -10 °C and 70 °C; the fluid temperature is controlled by the instrument regulating. The heating of an immersion heater and the cooling power is provided by a refrigeration system, obtaining temperature stability of 0.02°C over the working range.

4. Experiments

4.1 Instruments

4.1.1 Chilled Mirror Hygrometer

The dew-point temperature is directly measured by the chilled mirror hygrometer. When vapor begins to condense on a polished metal surface after being cold, the ambient air's water vapor content has reached its maximum saturation. The temperature of the metal surface and the saturation vapor pressure of the water vapor can be combined to calculate the relative humidity (the value is taken from a table: absolute humidity and saturation vapor pressure as a function of temperature). The primary purpose of this technique is calibration. [11]

4.1.1.1 Operation of Chilled Mirror Hygrometer

The dew-point approach includes cooling a surface to a temperature where water on the mirror surface is in equilibrium with the water vapor pressure in the gas sample above the surface. The surface in question is often a metallic mirror. The mass of water on the surface is not growing (due to the surface being too cold) nor shrinking at this temperature (too warm a surface).

The chilled-mirror approach involves building a mirror out of a material that has strong thermal conductivity, like silver or copper, then correctly plating it with an inert metal, like iridium, rubidium, nickel, or gold to prevent tarnishing and oxidation. A thermoelectric cooler is used to cool the mirror until the first signs of dew appear. Photodetector tracks reflected light after a beam of light, often from a solid-state broadband light emitting diode, is directed to the mirror surface.

Dew droplets develop on the chilled mirror's surface when the gas sample travels across it, scattering the reflected light. The photodetector output diminishes as the amount of reflected light decreases. Through an analog or digital control system, this in turn regulates the thermoelectric heat pump to keep the mirror temperature at the dew point. The mirror temperature is monitored at the established dew point by a precision micro platinum resistance thermometer (PRT) suitably placed in the mirror.

The sensor is detecting the dew point if the mirror is set to an equilibrium condition above the ice point, or 0°C. Since the deposit cannot remain liquid for very long below 0 °C, it is presumed to be frost and that the sensor is detecting the frost point. The only real way to confirm that the sensor is controlling on the frost point is to visually inspect the mirror using a microscope. However, if the mirror is kept incredibly clean, it is conceivable for dew to exist below 0°C. However, it is usually impractical to keep a mirror completely clean, especially outside, as impurities like spores and other particulates behave as motes on which frost deposits might form. As a result, errors caused by dew/frost point confusion at 0°C are uncommon. [12]

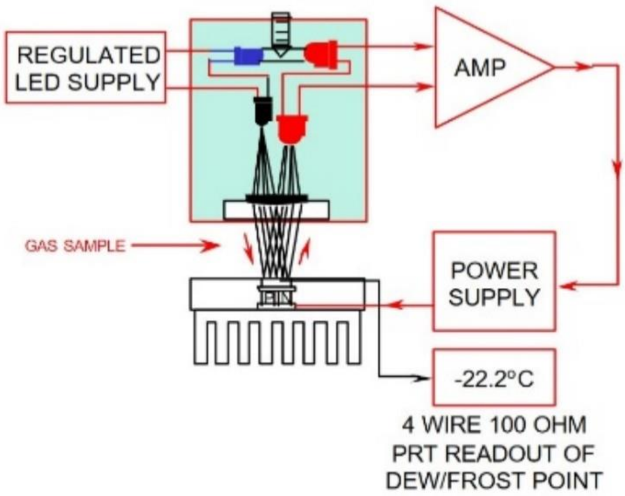


FIGURE 5 - BLOCK DIAGRAM OF CHILLED MIRROR HYGROMETER WORKING PRINCIPLE

The Chilled mirror hygrometer used in our experimentation is Dew Point Mirror 573

FIGURE 6 - EXPERIMENTAL SET UP OF MBW 573 CHILLED MIRROR HYGROMETER

The 573 Dew Point Mirror is a high-performance 19" rack format device featuring an integral measurement head, pressure sensor, sample pump, and flow meter for continuous, accurate monitoring of frost/dew point and absolute humidity values across a variety of applications.

4.1.2 Rotronics RH Sensor

An RH sensor is a piece of technology that gauges the humidity in its surroundings and turns the results into an electrical output. Size and functionality of humidity sensors vary greatly; some are available in portable devices (like smartphones), while others are integrated into bigger embedded systems (such as air quality monitoring systems). In the field of meteorology, humidity sensors are frequently utilized.

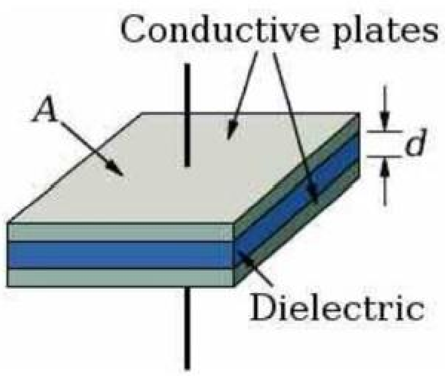


FIGURE 7 - WORKING OF RH SENSOR

A hygroscopic dielectric material sandwiched between two electrodes makes up the humidity sensor, a tiny capacitor. With a typical dielectric constant range from 2 to 15, plastic or polymers are typically used as the dielectric material in capacitive sensors.

This constant, along with the sensor geometry, determines the capacitance value when there is no moisture in the sensor. The dielectric constant of water vapor at standard ambient temperature is approximately 80, which is significantly higher than the dielectric constant of the sensor material. As a result, the sensor capacitance rises as a result of moisture absorption. At equilibrium, ambient temperature and water vapor pressure affect how much moisture is present in a hygro-scopic medium. This holds true for the sensor's hygroscopic dielectric substance as well.

According to definition, relative humidity depends on both the surrounding temperature and the water vapor pressure. Relative humidity, the amount of moisture in the sensor, and sensor capacitance are all directly correlated.

The operation of a capacitive humidity instrument is based on this relationship.

Relative humidity is the ratio of the actual water vapor pressure present to the highest water vapor pressure (saturation vapor pressure) that is feasible at a specific temperature, as we recall from our relative humidity basics. The rate of variation in the dielectric substance is correlated with the change in relative humidity. [13]

4.1.3 Thermometer

PRT is Platinum Resistance Thermometer. The PRT probe is made from platinum that uses a resistance vs temperature relationship. It is a synonym for resistance thermometer.

Resistance thermometers work by changing resistance with a change in temperature in a repeatable manner. Resistance thermometers are made from a length platinum that is either wrapped around a ceramic or glass core or has been deposited on a ceramic base. All resistance thermometers manufactured by Peak Sensors comply to international standards as defined in IEC 60751:2008 (Industrial Platinum Resistance Thermometer Sensors).

FIGURE 8 - PRT TEMPERATURE SENSOR

The most popular kind of platinum resistance thermometer is one with PT 100 temperature sensors. Resistance thermometers are frequently referred to as Pt100 sensors, even though they may not actually be of that type. Pt stands for platinum, which is what the sensor is constructed of (Pt). The number 100 denotes the sensor's resistance, which is 100 ohms at 0°C.

One kind of temperature sensor is a resistance thermometer. It comprises of a component that gauges temperature through resistance. RTDs (short for resistance temperature detector), RT, Pt100, and Pt1000 are common names for resistance thermometers. Pt100 probes can be protected in a variety of ways, and temperature sensors are made to provide the most accurate readings. [14]

4.2 Software's

4.2.1 2500 Controllog Windows Based Automation And Control Software

A Thunder Scientific 2500 Humidity Generator is fully automated by the 2500 ControLog, and numerous devices can be connected through a variety of interfaces. Data from the generator and any attached devices is automatically retrieved and stored for real-time or post-processing display in either a numerical or graphical format. Using HumiCalc with Uncertainty, ControLog calculates the Uncertainty of the 2500 produced parameters in real time. The various important functions of this software are [10]:

- **Auto Profiling and assurance conditions:** To fully automate the functioning of the Thunder Scientific 2500 Humidity Generator, Auto Profiling uses a predefined list of setpoints known as a profile. The generator is automatically managed using an Auto Profile as a road map. The profile specifies the setpoint values to use, the rate at which to transition from one setpoint to the next, and the amount of time to spend at each setpoint before moving on to the next. Assurance Before allowing the profile to proceed, the user can check that a certain measured value is within a given tolerance and/or stability using the conditions established in the profile.

- **Graphing:** A strong tool for viewing previously collected data or for real-time data monitoring is graphing. The data tabs and the graph work together seamlessly. The most recent data points from the linked devices are stored in data tabs at the chosen interval while the generator is running. This saved data can be represented graphically using a graph. To present the data in various ways, each graph tab can be adjusted.
- **Data Logging:** Individual Data Tabs are used by ControLog to store data. Each data tab has a spreadsheet-style view that lists the measured data items that correspond to each date/time stamp as well as a date/time stamp and the time stamp itself. Data tabs are divided into three categories: Device Data, File Data, and Data Summary. Even though all three types have the same spreadsheet-style display and functionality, they all come from different data sources.
- **Device Connections:** ControLog supports a customizable interface that works with most ASCII based serial or GPIB devices. ControLog allows the user to define the ASCII commands that are sent and/or received through the interface to communicate with the device. The system supports both “request to receive” type of communication as well as the “receive only” type of communication. ControLog can also log analog signals using an Agilent® 34970A Data Acquisition/Switch Unit. In addition to the above options, ControLog also offers a Manual Connection that allows the user to manually record data items for a device that either has no interface or has an interface that is not supported by ControLog. [10]

4.2.2 Version R2 - Gecko Software

All MBW products and Thunder humidity generators can be used with Gecko R2, an internal program developed by MBW. It provides users with adjustable channels, scaling, and statistical analysis to visualize measurement data numerically and graphically. It comprises automatically collected data. All conceivable measurement variables, including serial numbers and time-date data, are immediately logged to a log file whenever an instrument is connected. The ability to specify humidity and temperature set points is a feature that is incorporated, allowing compatible humidity generators or temperature equipment to be configured to execute automatic calibration profiles. Because set point control and automatic data acquisition are available, engineers may fully automate calibration. It is possible to create data files that display both the generated value and the measured value from the hygrometer. [7]

4.2.3 HumiCalc

HumiCalc software assures user simple work of complex humidity conversions.

4.2.4 . MS Excel

All the data obtained from the above software's was elaborated and analyzed using various tools on MS Excel.

5. Experiment and Investigation

5.1. Method Used

A flow of gas at an elevated pressure is saturated with respect to the liquid or solid phase of water in an ideal two-pressure system, and it is then isothermally extended to a lower pressure. The resultant humidity content of the expanded gas stream can be accurately determined by taking measurements of the pressure and temperature of the saturated gas stream as well as in the test chamber following expansion.

It is common practice to produce a range of relative humidity values at set temperatures using a two-pressure generator. Typically, the saturator and chamber are in thermal equilibrium and share a shared bath. In this instance, using the simplified approximation, the relative humidity produced is mostly based on the ratio of the observed saturated gas stream pressure (saturation pressure) to the measured chamber pressure. [2]

$$\%RH = \frac{P_C}{P_S} \times 100$$

EQUATION 4 -- RELATIVE HUMIDITY AS THE RATIO OF PRESSURES

Where, P_C is the chamber pressure, absolute

P_S is the saturation pressure, absolute

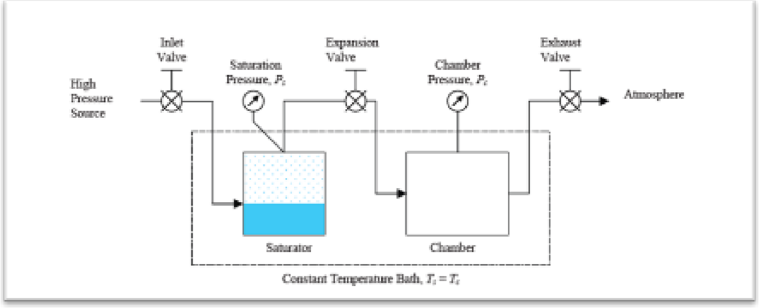


FIGURE 9 - SCHEMATIC DIAGRAM OF TWO PRESSURE METHOD WHERE T_S = T_C

By precisely measuring the temperatures of the saturator and chamber rather than relying on idealized assumptions of equality, the accuracy of a two-pressure generator can be significantly improved. Observing the figure demonstrated below, a stream of gas is saturated with respect to the liquid or solid phase of water at a specific saturation temperature while flowing at a high pressure. The gas stream is subsequently extended to an alternate temperature and lower pressure. This method additionally employs a pre-saturator to guarantee complete saturation.

It is important to adequately calculate the produced humidity in the test chamber are measurements of the pressure and temperature of the saturated gas stream (Ps and Ts), as well as in the test chamber following expansion (Pc and Tc). [9]

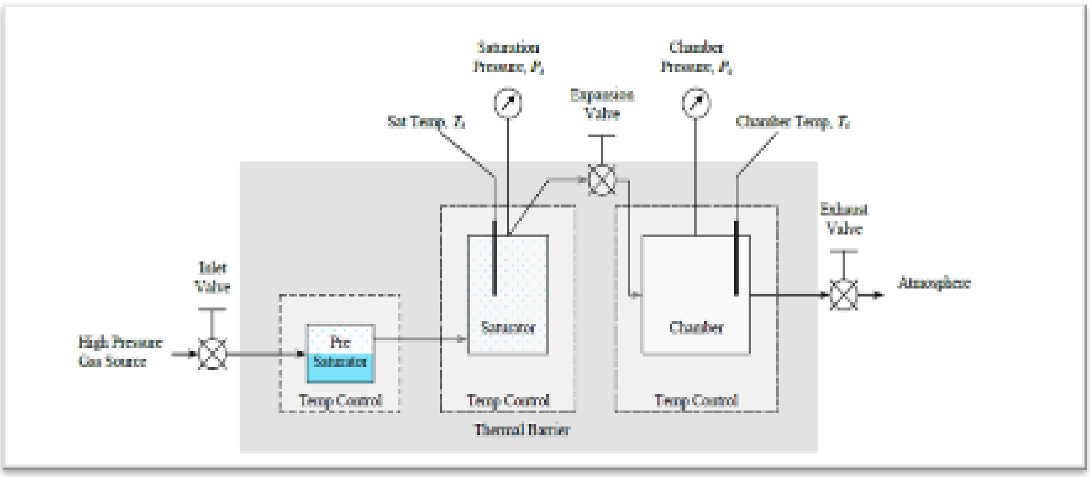


FIGURE 10 - SCHEMATIC DIAGRAM OF TWO PRESSURE METHOD

A thermal barrier separating the saturator and chamber temperature control portions is shown in the diagram. To keep things simple, the saturator and chamber are frequently kept at the same temperature via a shared temperature-controlled medium. While doing so makes the design simpler

Independent readings of the saturation and chamber temperatures must still be taken and used to calculate the relative humidity of such a system. The relative humidity formula can then be applied using the four independent measurement parameters of saturation temperature, chamber temperature, saturation pressure, and chamber pressure.

$$\%RH = \frac{P_C}{P_S} \times \frac{F_S}{F_C} \times \frac{E_S}{E_C} \times 100$$

EQUATION 5 - RELATIVE HUMIDITY USING FOUR INDEPENDENT MEASUREMENT PARAMETERS

Where,

Pc is the absolute chamber pressure

Ps is the absolute saturation pressure

Ec is the saturation vapor pressure computed at the chamber temperature

Es is the saturation vapor pressure computed at the saturation temperature

Fc is the enhancement factor computed at the chamber pressure and temperature

Fs is the enhancement factor computed at the saturation pressure and temperature

All additional humidity characteristics, including dew point, frost point, parts per million by volume, and others, can be calculated from the four temperature and pressure parameters.

5.3 Experimentation set-up

5.3.1 Calibration of thermometers:

10 thermometers were calibrated at the same time, in same bath against same reference thermometer.

FIGURE 11 - CALIBRATION OF THERMOMETERS

5.3.2 Mounting of thermometers and RH sensor's to the walls of chamber:

Once the thermometers were calibrated, they were carefully mounted over the full volume of the test chamber using the supports. The 2 RH sensors are mounted at the center of the test chamber to verify the changes in the obtained dew point. The thermometers were then carefully positioned throughout the test chamber, about 1 to 2 inches from each corner (8 total probes), and 2 inches to the left and right of the center (2 probes total).

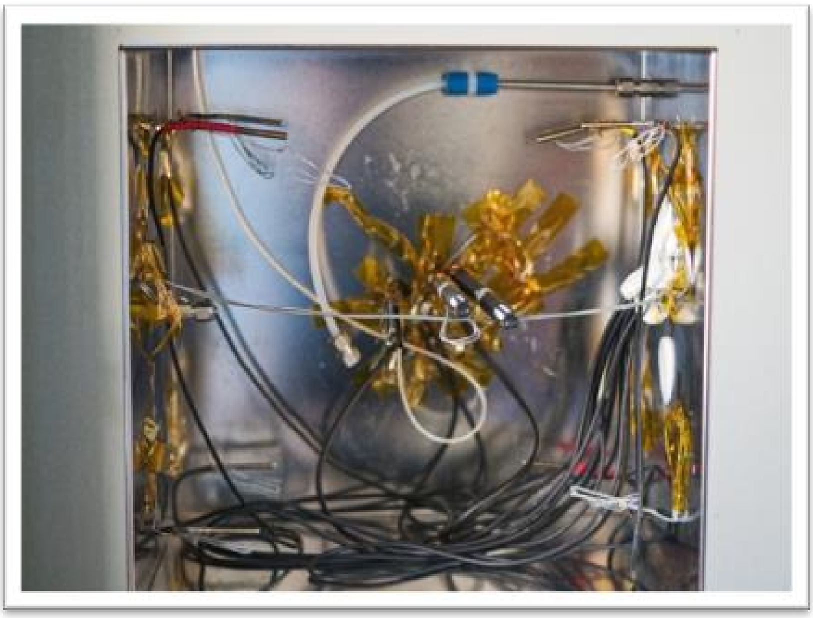


FIGURE 12 - IMAGE REPRESENTING THE MOUNTED SENSORS

After the thermometers are mounted to the walls of the chamber, The system is well insulated by a thermal barrier and the door is closed.

The chamber dimensions are H 15" (381 mm) W 15" (381 mm) D 12" (305 mm) [9]

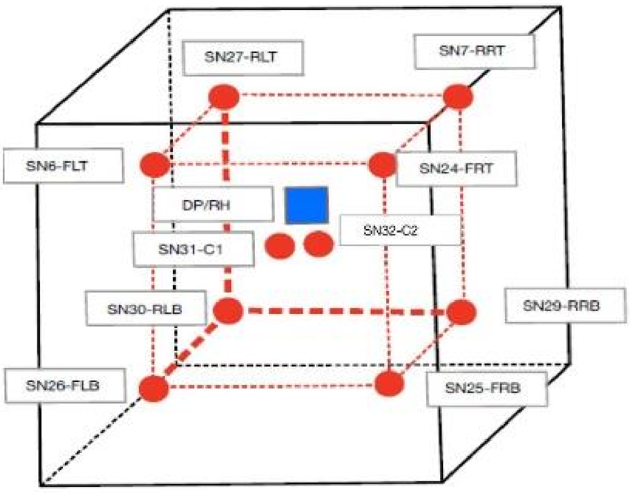


FIGURE 13 - SCHEMATIC REPRESENTATION OF THE POSITION OF SENSORS IN THE TEST CHAMBER

5.3.3 Filling the chamber with water:

Approximately 1 gallon (3.8 Liters) of double distilled water was filled in the generator using right knob at the right side on the top of generator. The consumption of water depends on the temperature and humidity at which the generator was operated.

The water levels were constantly monitored and filled in as per requirement.

5.3.4 Auto profiling and data acquisition:

An auto profile was drafted for various flow rates, relative humidity, and temperatures. The generator was operated at relative humidity levels of 10 %, 30 %, 50 %, 70 %, 90 % and 95 %. The three flow rates inside the chamber at which the generator was operated were $5\left(\frac{\mathrm{l}}{\mathrm{min}}\right)$, $12\left(\frac{\mathrm{l}}{\mathrm{min}}\right)$ and $20\left(\frac{\mathrm{l}}{\mathrm{min}}\right)$. The measurements were carried out on 6 different temperatures. The generator was allowed to stabilize for a minimum of two hours at each temperature listed. The software, 2500 Control Log-Thunder Scientific was used in auto profiling, acquisition of data and saving the acquired data.

5.3.5 Connecting the Chilled mirror hygrometer

The chilled mirror hygrometer which was placed above the generator was connected with the thermometers and all the flow ports. The data from hygrometer with respect to dew points, frost point, temperature of the thermometers etc. was acquired on Gecko R2 software.

The mirror was constantly cleaned using water and alcohol to remove any condensate, dust, or residue on the mirror.

Now, once the set-up was complete the connections were made, and the generator was turned on to obtain the results.

FIGURE 14 - CHILLED MIRROR HYGROMETER

5.3.6 Experimental timeline

23/11/2021	Experiment begin date
25/11/2021	Mirror cleaning done and poured distilled water as level of water was reduced
6/12/2021	Mirror cleaning done and poured distilled water as level of water was reduced
9/12/2021	Remounted the RH sensors and thermometers inside the chamber due to disturbance in position of sensors within the chamber
9/12/2021	Mirror cleaning done and poured distilled water as level of water was reduced
9/12/2021	Experiment end date

TABLE 1 - TIMELINE OF THE EXPERIMENT

5.4 Parameters investigated

5.4.1 Chamber Temperature

5.4.1.1 Chamber Temperature Definition

A temperature chamber can simulate the environmental conditions that a generator will experience while operating.

5.4.1.2 Cable length of temperature probes inside the chamber temperature

The location of the temperature measurement in the chamber should be quite close to any humidity measurement equipment being tested. When evaluating a variety of humidity equipment, the group typically uses the central site. If the chamber is large enough, adding more cable inside may reduce the thermometer stem effect. This isolates the thermometer element from the temperature outside the chamber due to the physical length of the cable. If at all possible, it should be thought about using thinner, more compact wires for the thermometer and any humidity testing equipment to lessen the effect of heat piping. Less heat will be transferred thermally through the wires connecting the inside and exterior of the chamber as a result. Extreme care was taken to keep the chamber thermometer's cable at an acceptable minimum length.

5.4.1.3 Temperature uniformity of chamber temperature

Even though it is commonly disregarded, relative humidity is strongly affected by temperature. Humidity gradients are produced by thermal gradients in the chamber and are inversely proportional to relative humidity. As a result, it's critical to take safety measures to ensure the chamber's temperature remains constant. Temperature measurement must be done with exact accuracy when generating parameters, such as dew point. [15]

5.4.2 Dew point and Frost Point

Dew Point is the temperature to which a volume of gas must be cooled such that it becomes saturated with respect to liquid water.

Frost point is the temperature to which a volume of gas must be cooled such that it becomes saturated with respect to ice. [4]

Relative humidity is connected to the dew point and frost point. It is implied by a high relative humidity that the dew point is approaching the air temperature. A relative humidity of 100 percent indicates that the air is completely saturated with water vapor and that the dew point is equal to the present temperature in the air. The closer the dew point is to the temperature, the higher the relative humidity. It is important for the analysis of dew point measurements as it determines the amount of moisture present. Although it is commonly referred to as the "DP of the air," this feature of the vapor could also apply to the "air parcel," or the small mass of mixing of dry air and vapor taken into consideration.

5.4.3 Relative Humidity

The ratio of the air's vapor pressure to its saturation vapor pressure is used to define relative humidity. The amount of water vapor in an air-water mixture relative to the maximum amount is known as relative humidity (RH). RH is a comparison between a specific water-air mixture's humidity ratio and the saturated humidity ratio at a particular temperature.

RH is particularly sensitive to temperature fluctuations and has a strong relationship to temperature. This implies that your RH will be stable if your system's temperature is stable. Relative humidity is affected by system pressure in addition to temperature.

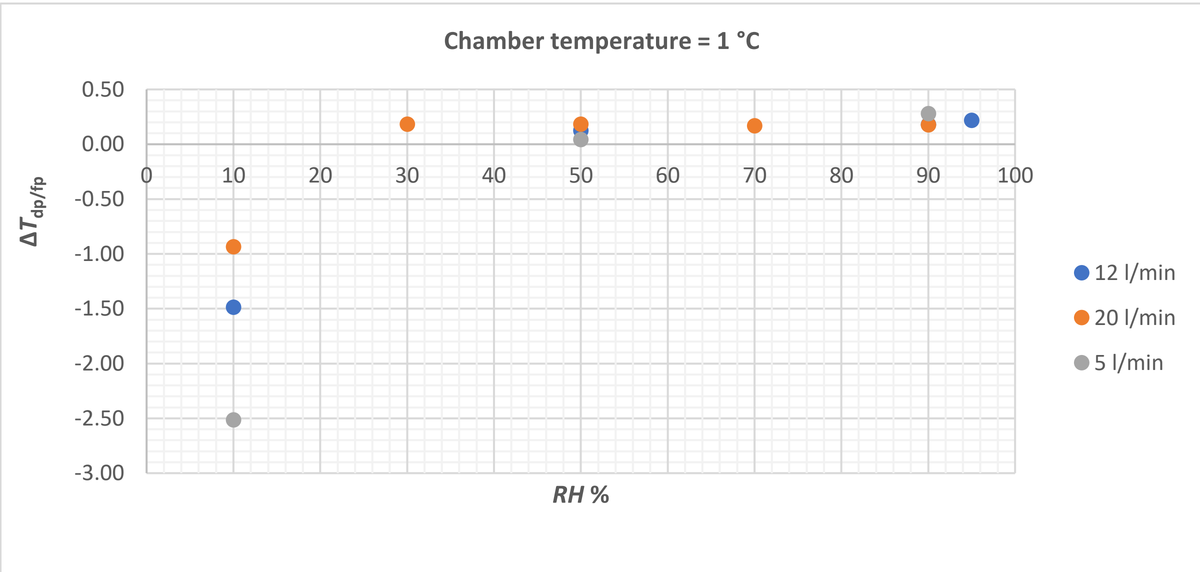
We use relative humidity to quantify the amount of water vapor present in the atmosphere. It informs us of the air's water vapor content in relation to the maximum amount that air could carry under certain conditions. A percentage is used to denote relative humidity. [4]

5.4.4 Parameters investigation results

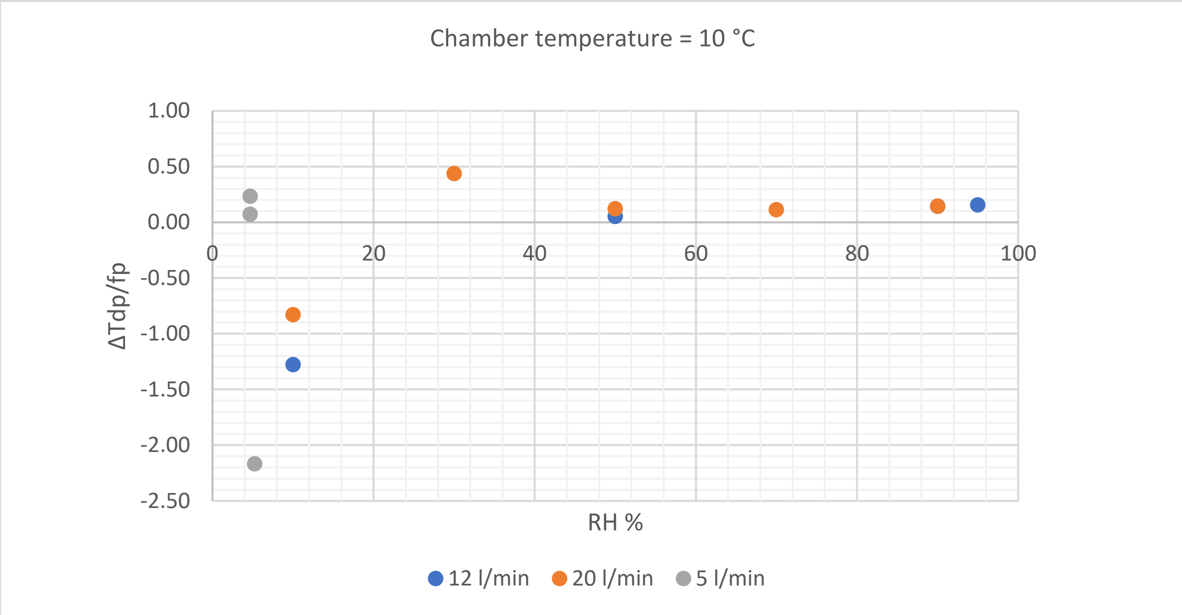
Once the experiment was concluded. From the software's 2500 Control Log and Version R-2 Gecko which have recorded the data from generator and chilled mirror hygrometer respectively is extracted. The extracted data is further analyzed to understand the behavior of each characteristic.

The graphical representation of the investigated results in illustrated.

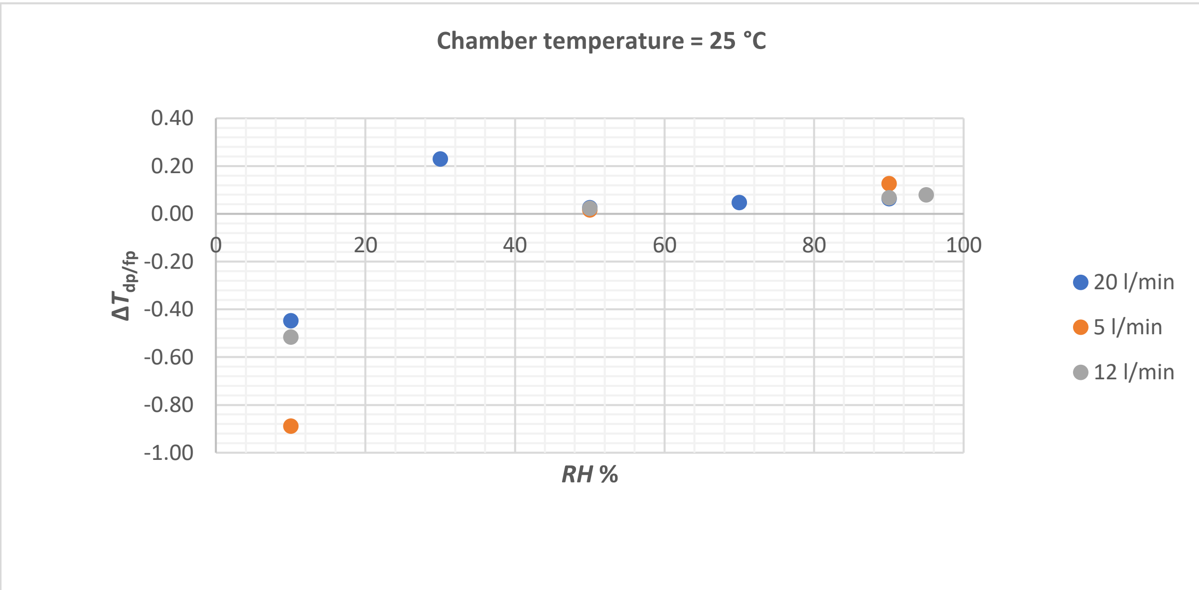
The graphical representation of the difference between the dew point or frost point generated in the chamber temperature and the measured dew point or frost point with respect to different humidity levels at 3 different flow rates.



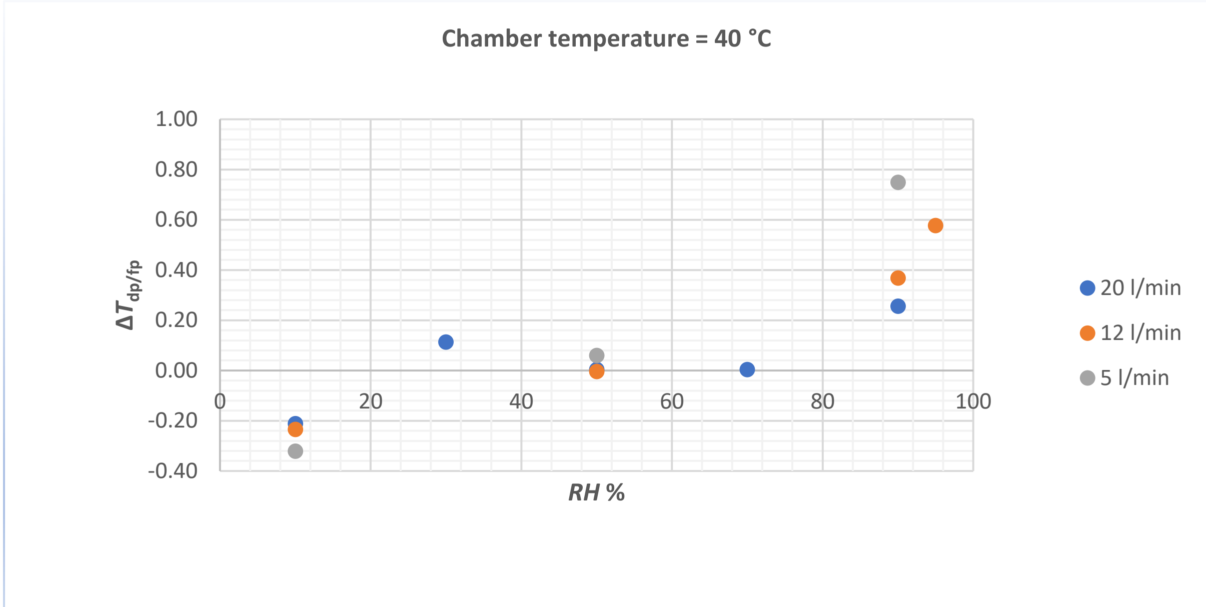
Graph 1: Representation of $\Delta T_{dp/fp}$ versus RH % at chamber temperature 1 °C



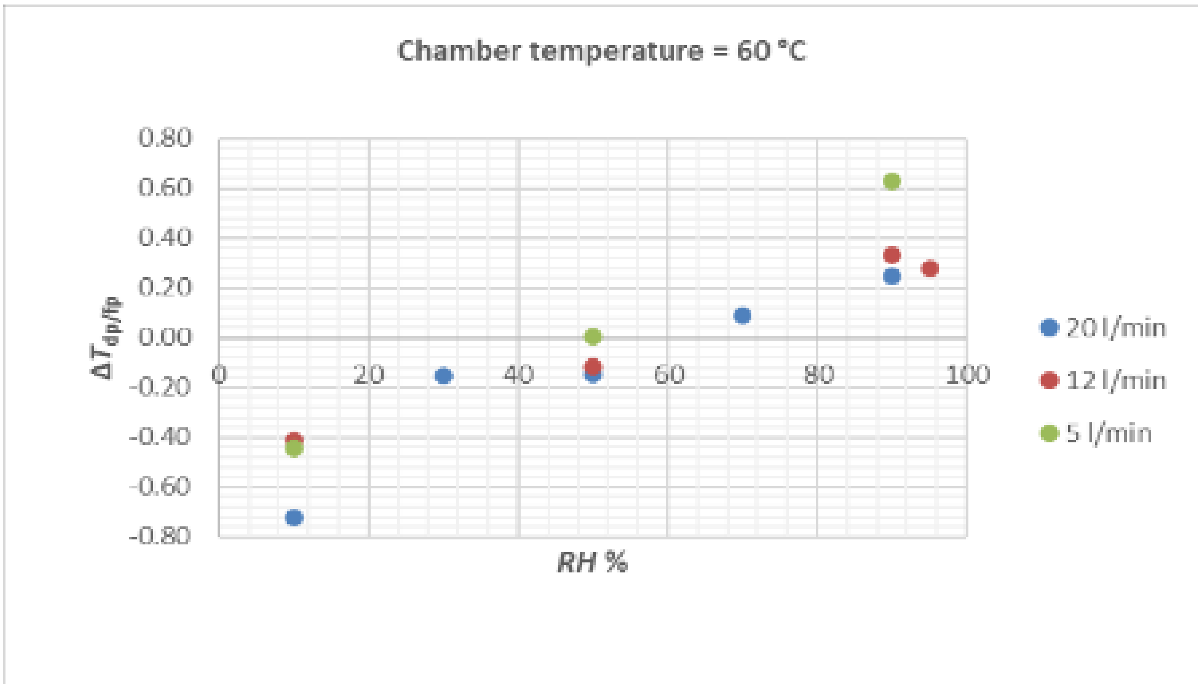
Graph 2: Representation of $\boldsymbol{\Delta T}_{\mathbf{dp/fp}}$ versus ***RH* %** at chamber temperature 10 °C



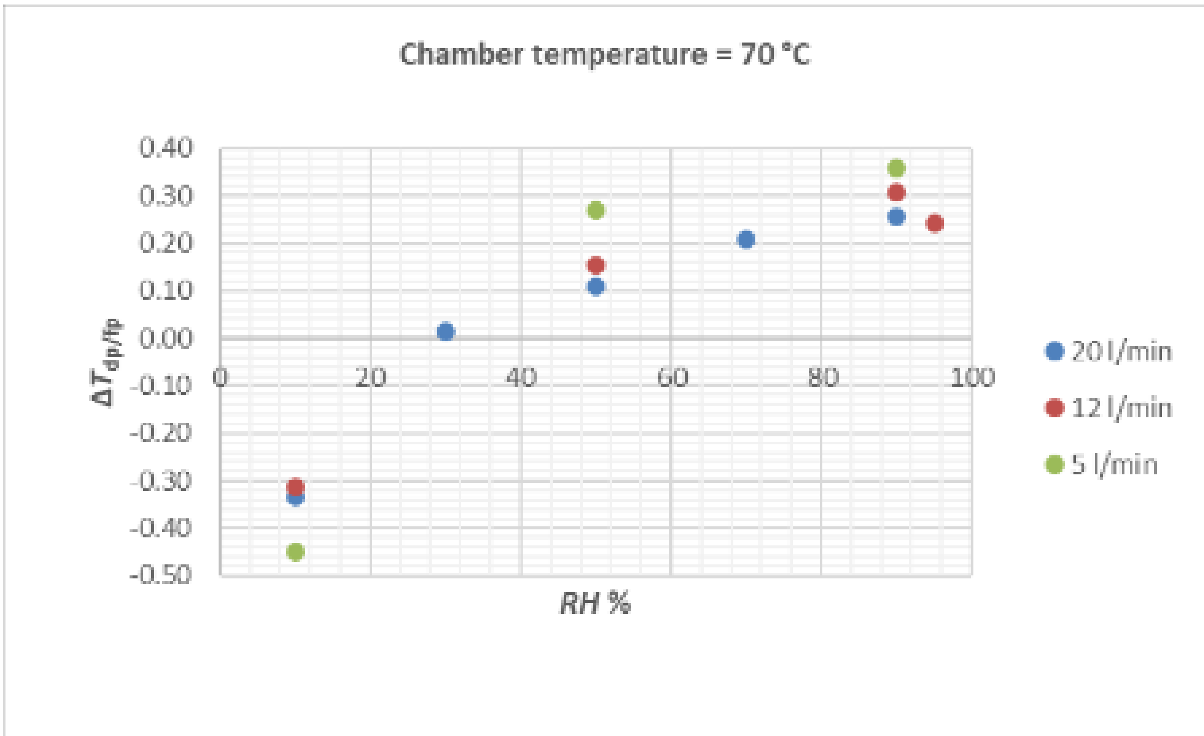
Graph 3: Representation of $\boldsymbol{\Delta T}_{\mathbf{dp/fp}}$ versus ***RH* %** at chamber temperature 25 °C



Graph 4: Representation of $\boldsymbol{\Delta T_{\mathrm{dp/fp}}}$ versus ***RH* %** at chamber temperature 40 °C



Graph 5: Representation of $\boldsymbol{\Delta T_{\mathrm{dp/fp}}}$ versus ***RH* %** at chamber temperature 60 °C



Graph 6: Representation of $\boldsymbol{\Delta T_{\mathrm{dp/fp}}}$ versus $\boldsymbol{RH}$ **%** at chamber temperature 70 °C

6. Uncertainty evaluation

6.1 Introduction

It is required to provide quantitative evidence of the result's quality when reporting the outcome of a physical quantity measurement so that the measurand can be given a range of plausible values. Measurement results cannot be compared without this information, either among themselves or to reference values provided in a specification or standard. Therefore, it is essential that there be a method for describing the quality of a measurement result that is simple to use, clear to understand, and widely acknowledged. [16] [1]

A measurement result is defined as "a set of quantity values being attributed to a measurand coupled with any other available relevant information" by the international vocabulary of metrology (VIM)[1]. A single measured quantity value and a measurement uncertainty are typically used to indicate a measurement result. Based on the data used, the measurement uncertainty is a non-negative metric that describes the dispersion of the quantity values being attributed to a measurand. Since the measurement result may not accurately reflect the value of the measurand, the uncertainty quantifies this uncertainty.

There are a number of potential sources of uncertainty in a measurement, including an incomplete definition of the measurand, an imperfect realization of the definition of the measurand, insufficient knowledge of the impacts of environmental variables on the measurement, or inaccurate assessment of environmental factors. A personal bias in reading analog instruments, a finite instrument resolution or discrimination threshold, inaccurate values for measurement standards and reference materials, and variations in repeated observations of the measurand under seemingly identical circumstances are some other potential sources of uncertainty.

Most of the time, a measurand, represented by Y, is calculated from N other values, denoted by X_1, X_2 , X_3 , ...X_N , through a functional relationship f:

$$Y = f(X_1, \dots\dots, X_N)$$

EQUATION 6 – MEASURAND

Therefore, the estimate y of Y is given by:

$$y = f(X_1, \dots \dots ., X_N\ )$$

EQUATION 7 - ESTIMATE OF MEASURAND

where $x_1, \dots\ , x_N$ are the estimates of the input quantities $X_1, \dots, X_N$.

The standard deviation of the estimate y, termed combined standard uncertainty, $u_c(y)$, is then obtained by combining the standard deviation of the input estimates $X_1, X_2, X_3, \dots, X_N$ denoted by $u(x_i)$.

$$u_c(y) = \sqrt{\sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i)}$$

EQUATION 8 - COMBINED STANDARD UNCERTAINITY

Where $\left(\frac{\partial f}{\partial x_i}\right)$ is the sensitivity co-efficient. This quantity describes how the estimates y varies with changes in the values of the input estimates x_i and $u(x_i)$ is the standard uncertainty (Defined as standard deviation) associated with x_i.

If the input quantities $X_1, X_2, X_3 \dots, X_N$ are not independent in the equation below, co-relation coefficients must be considered in the below equation.

$$u_c(y) = \sqrt{\sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} \left(\frac{\partial f}{\partial x_i}\right)\left(\frac{\partial f}{\partial x_j}\right) u\ (x_i, x_j)}$$

EQUATION 9 - COMBINED STANDARD UNCERTAINITY WITH ALL PARAMETERS

The estimates x_i and their standard uncertainties $u(x_i)$ are determined, in turn by considering thedistribution of possible values of the quantities $X_{i.}$

Type A assessment of the standard uncertainty components is performed if the probability distribution of the values is based on several observations of X_i

(frequency based), and Type B evaluation is used if the distribution of X_i values is known in advance.

In the case of a Type A evaluation of standard uncertainty, the estimate X_i can be determined as the arithmetic mean or average of n independent observations as follows [16]:

$$x_i = \bar{X}_i = \frac{1}{n}\sum_{k=1}^{n} X_{i,k}$$

EQUATION 10 - TYPE A ARITHMETIC MEAN

While the standard uncertainty u(xi)is given by the experimental standard deviation and is calculated as:

$$|u(x_i) = s(\bar{X}_i)| = \sqrt{\frac{1}{n.(n-1)}\sum_{k=1}^{n}\left(X_{i,k} - \bar{X}_i\right)^2}$$

EQUATION 11 - EXPERIMENTAL STANDARD DEVIATION

If the estimate x_i of the quantity X_i is not obtained from repeated observations, its standard uncertainty $u\ (x_i)$ is estimated using a Type B evaluation, that is an evaluation based on the available information on the variability of X_i . Examples of this type of information include data from calibration certifications, manufacturer's specifications, and historical experience with the measurements. The calibration certificate's uncertainty is typically expressed as an expanded uncertainty.

According to the Guide on the Expression of Uncertainty in Measurement $(GUM)^2$, the expanded uncertainty is used to provide a range that can include a larger percentage of the measurement results. The fraction is influenced by the measurement probability distribution function's level of confidence or coverage factor, k. Accordingly, depending on the coverage factor, the enlarged uncertainty, $U(y)$, is a multiple of the combined uncertainty.

For instance, if measurement results are placed in the Gaussian distribution's normal probability distribution function, 68 percent of the statistical data will be in this distribution 99.7 percent will set in three standard deviations of the mean, 95 percent will lie in two standard deviations of the mean. [16]

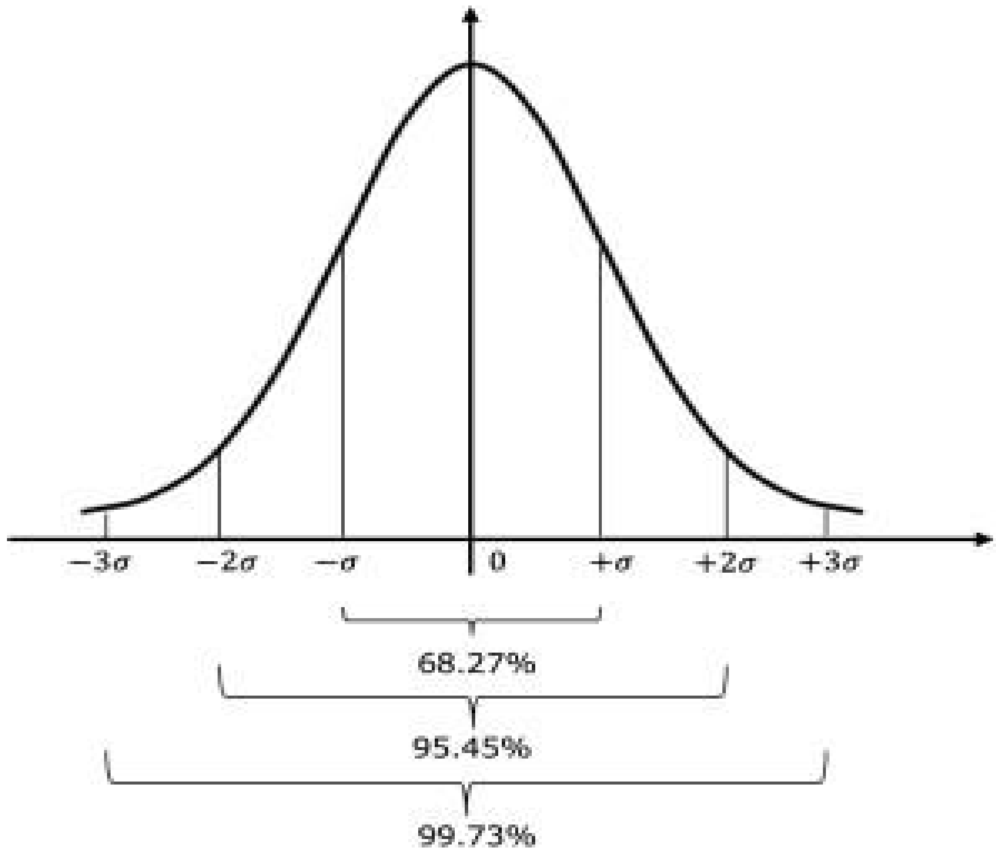


FIGURE 15 - NORMAL PROBABILITY DISTRIBUTION AND CONFIDENCE LEVELS, K = 1 (68 %), K = 2 (95 %), K = 3 (99.7 %)

6.2 Uncertainty evaluation of the generator

6.2.1 Definitions

The Chamber Temperature Uniformity for a Model 2500 Humidity Generator is discussed here. The degree of temperature uniformity within the test chamber directly affects the relative humidity gradients. Ten thermometers of the same type and nominal resistance were calibrated collectively over the temperature range of -70°C to 180°C to determine the homogeneity of the chamber temperature. The thermometers were then carefully positioned throughout the test chamber, about 1 to 2 inches from each corner (8 total probes), and 2 inches to the left and right of the center (2 probes total). [15]

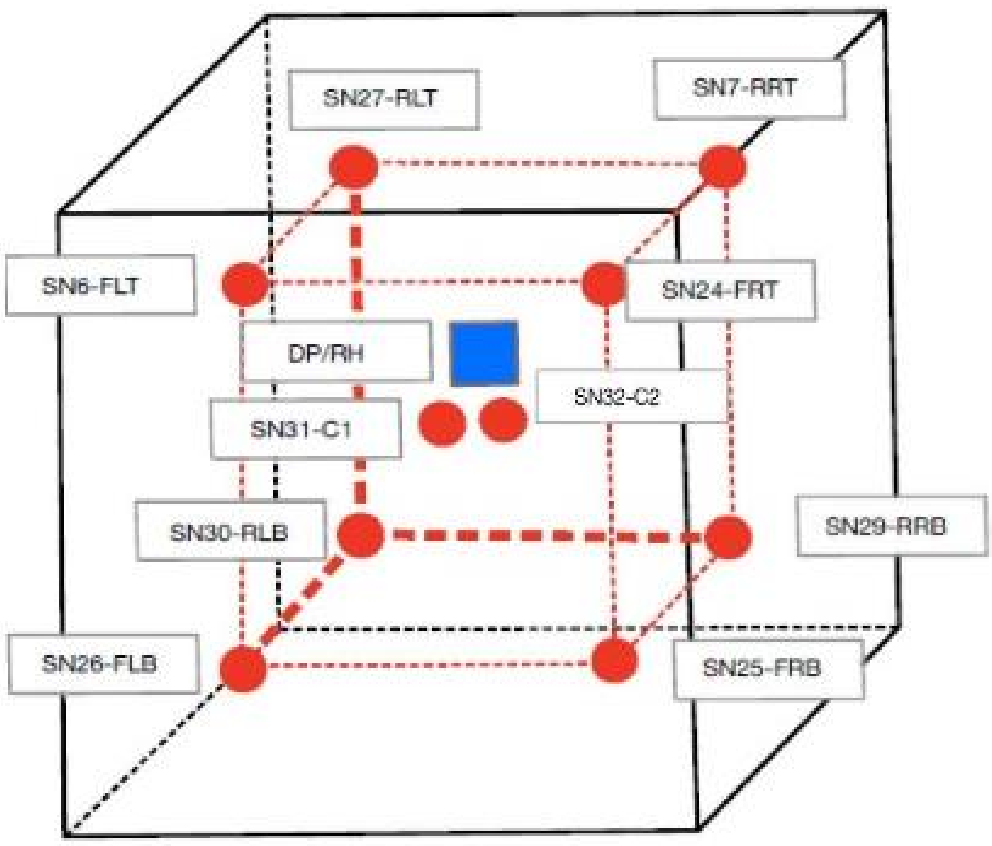


FIGURE 16 – SCHEMATIC REPRESENTATION OF SENSORS IN THE CHAMBER

By noting the highest and lowest readings from the probes placed the center of the chamber at the same time and dividing the difference by two, the maximum measurement deviation from the mean can be calculated.

6.2.2 Maximum absolute Deviation and Standard Uncertainty due to temp uniformity

6.2.2.1 Maximum absolute deviation

We obtain specific set of values of temperatures from the thermometers placed throughout the chamber and the reference thermometers. These values are the temperatures that are recorded over the course of experiment. We will calculate the mean value for each temperature range and check for its deviation. Once we have the deviations, we will convert them to absolute values and check for the maximum among them, this will give us the maximum absolute deviation.

The maximum absolute deviation is always calculated with respect the PRT placed in the middle of the volume. In our case it is the sensor 31 placed in the center of the chamber.

Keeping this as reference we calculated the mean value at each temperature range, then we obtained the mean value of each temperature range for each PRT.

After this, we selected the maximum of these values and subtracted it from the mean reference thermometer (Sensor 31).

Below is the table with the different maximum absolute deviation values throughout the operating range of the temperatures in the chamber.

Temperature (°C)	Absolute maximum deviation
1	0.105
10	0.011
25	0.014
40	0.016
60	0.054
70	0.155

TABLE 2 - ABSOLUTE MAXIMUM DEVIATION AT DIFFERENT TEMPERATURES

6.2.2.2 Standard Uncertainty due to temperature uniformity

Standard Uncertainty due to temp uniformity is calculated by dividing the maximum absolute deviation by root 3. This uncertainty component is determined using a rectangular distribution of the half-interval.

Temperature (°C)	Standard uncertainty due to temperature uniformity
1	0.061
10	0.007
25	0.008
40	0.009
60	0.031
70	0.089

TABLE 3 - STANDARD UNCERTAINTY DUE TO TEMPERATURE UNIFORMITY AT DIFFERENT TEMPERATURES OF THE EXPERIMENT

6.3. Uncertainty Components

The components of uncertainty of the measurement of temperature and relative humidity using the reference measuring devices, the uncertainties arising from the indicating devices of the climatic chamber, the contributions of the temporal and spatial distributions in the useful volume as well as the loading effects.

6.3.1. Spatial Uncertainty

The spatial inhomogeneity is determined as the maximum deviation of the relative humidity or temperature of a corner or wall measuring location according to DIN EN 60068-3-5 or DIN 50011-12, respectively, from the reference measuring location. It is equivalent to the half-width of a rectangularly distributed contribution with the expected value 0. [16]

$$u(\delta\, T_{inhom}) = \frac{1}{\sqrt{3}} \times Max\left|T_{ref} - T_i\right|$$

EQUATION 12 – SPATIAL UNCERTAINTY

Temperature (°C)	Spatial Uncertainty
1	0.137
10	0.104
25	0.060
40	0.232
60	0.360
70	0.289

TABLE 4 - SPATIAL UNCERTAINTY THROUGHOUT DIFFERENT TEMPERATURES OF THE EXPERIMENT

6.3.2. Radiation effect

The inner wall of the chamber always has a temperature that differs from the air temperature when the air temperature in the climatic chamber varies from ambient temperature. However, due to the heat exchange by radiation under these circumstances, bodies in the usable volume do not reach the ambient temperature.

When the air temperature in the climatic chamber varies from the ambient temperature, the inner wall of the chamber always has a temperature that is different from the air temperature. However, under these conditions, bodies in the useable volume do not achieve the ambient temperature because of the heat exchange by radiation.

100 % of the difference determined shall be allowed for as the half-width of a rectangular distribution as an uncertainty contribution to the air temperature. Hence the formula,

$$u(\delta\, T_{rad}) = \frac{1}{\sqrt{3}} \times Max|T_{le} - T_{he}|$$

EQUATION 13 - UNCERTAINTY CONTRIBUTION TO THE AIR TEMPERATURE

Where T_{le} is the PRT with low emissivity (Sensor 31)

Where T_{he} is the PRT with high emissivity (Sensor 32)

The radiation effect between the two thermometers sensor 31 and sensor 32 is tabulated below. [16]

Temperature (°C)	Radiation effect
1	0.009
10	0.006
25	0.005
40	0.009
60	0.012
70	0.012

TABLE 5 - RADIATION EFFECT BETWEEN THE TWO THERMOMETERS SENSOR 31 AND SENSOR 32

6.3.3 Uncertainty in temperature measurement resolution

Probe resistance is converted from analog to digital in a technique that can resolve temperature differences to 0.01°C. Consequently, the uncertainty component of temperature resolution is determined using a rectangular distribution of the half-interval.

$$u(R) = 0.01 \times \left(0.5\sqrt{3}\right)$$

$$\boldsymbol{u(R) = 0.0028}$$

EQUATION 14 - RESOLUTION OF TEMPERATURE MEASUREMENT

6.3.4 Uncertainty of the Temperature Reference Standard

The accuracy of the reference thermometer, according to the manufacturer, is $\pm 0.01°C$. The uncertainty of the temperature reference standard, $u(T_{ref})$, based on the rectangular distribution of interval is as shown below.

$$u(T_{ref}) = 0.01\sqrt{3} \text{ (Equation 9)}$$

$$\boldsymbol{u(T_{ref}) = 0.006}\text{°C}$$

EQUATION 15 - UNCERTAINTY OF THE TEMPERATURE REFERENCE STANDARD

6.3.5 Uncertainty due to Self-Heating of Chamber Temperature Probe

Although it is typically utilized in air, a well-stirred fluid bath is employed for calibration and verification of the chamber temperature probe. As a result, it is important to consider the probability of some self-heating with this measurement. Self-heating is thought to be +0.05% of reading when temperature measurements are made in degrees Celsius. The equation for the temperature uncertainty of self-heating, $u(SH)$, is then based on the rectangular distribution of interval.

$$u(SH) = 0.05\% \times \left(\frac{T_c}{\sqrt{3}}\right)$$

$$u(SH) = 0.00029 \times T_c$$

EQUATION 16 - UNCERTAINTY OF SELF-HEATING

Temperature (°C)	Uncertainty of self-heating of chamber temperature
1	0.000
10	0.003
25	0.007
40	0.012
60	0.017
70	0.020

TABLE 6 - UNCERTAINTY OF SELF-HEATING OF CHAMBER TEMPERATURE

7. Conclusion

The existence of water vapor in air or other carrier gases affects a wide range of physical, chemical, and biological processes. Numerous sectors recognize the need of accurate humidity measurements since the amount of water vapor in the air has a significant impact on costs, the quality of products, health, and safety.

The calibration of a relative humidity generator chamber is essential to determine the deviation of the characteristics of relative humidity and air temperature within the chamber volume. The performance of the generator fairly depends on these parameters. Hence it is essential to study the additional characteristics, such as inhomogeneities, stabilities, etc., are usually found to characterize the chamber and potential effects on the test material placed in the chamber. These data sets are important for estimating the measurement uncertainty of the calibration results and are of considerable relevance to the chamber user since they describe the features of the chamber in use. It is necessary to calibrate the indication for temperature and relative humidity by comparing it to the values for air temperature and air humidity as measured in the chamber using reference equipment.

We characterized the generator over the period of 23/11/2021 to 09/12/2021. The characterization was completed at 6 different temperatures. These temperatures were with respect to the relative humidity levels of 10 %, 30 %, 50 %, 70 %, 90 % and 95 % at 3 different flow rates.

The behavior of these parameters was analyzed from the experimental data to understand the characteristics of the generator and hence allowed us to determine the uncertainties components.

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