Measuring and Evaluating Relative Humidity (RH) and Temperature (T) for HSx Series Sensors

Introduction

This application note details the optimal methods for evaluating the performance of polymer-based capacitive relative humidity (RH) and temperature (T) HS4x and HS3x series sensors. It also describes the best practices for setting up measurements, methodologies for testing relative humidity and temperature accuracy, and data analysis techniques to assess sensor performance. The methods and practices outlined in this document ensure accurate data and reliable sensor characterization in various applications such as indoor air quality (IAQ), heating, ventilation, and air conditioning (HVAC), industrial; process control, and consumer electronics.

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1. Overview

Polymer-based capacitive relative humidity (RH) and temperature (T) sensors have emerged as essential components in a wide range of applications, including indoor air quality (IAQ) monitoring, heating, ventilation, and air conditioning (HVAC) systems, industrial process control, and consumer electronics. These sensors offer numerous advantages, such as their compact size, low cost, ease of integration onto printed circuit boards (PCBs), and compatibility with digital interfaces.

The core operating principle of these sensors rely on the capacitance change of a polymer dielectric material as it absorbs or desorbs moisture. This change in capacitance is directly proportional to the ambient relative humidity, enabling accurate measurement of RH levels. Additionally, these sensors incorporate a temperature-sensing element, based on the temperature dependence on the CMOS PTAT (Proportional To Absolute Temperature) principle, allowing for simultaneous measurement of both RH and temperature.

While polymer-based capacitive sensors offer significant benefits, their performance can vary depending on factors such as sensor design, manufacturing tolerances, environmental conditions, and measurement setup. Thus, thorough testing and evaluation are crucial to ensure accurate and reliable data in real-world applications. This application details the best practices for characterizing the performance of these sensors, ensuring the accuracy, linearity, stability, and overall performance of the polymer-based capacitive RHT sensors, and enabling optimal sensor utilization.

The following sections cover environmental chamber selection and setup, instrumentation, accuracy testing methodologies, data analysis techniques, and additional considerations to ensure comprehensive sensor evaluation.

2. Test Environment, Measurement Setup and Instrumentation

- **Controlled Environment**: Use temperature/humidity-controlled or stability chambers to create stable and reproducible test conditions.
- **Calibration and Validation**: Regularly calibrate and validate the chamber and/or the reference device using trusted instruments (for example, chilled mirror hygrometers, precision thermometers) or regularly calibrated transfer standards.
- **Sensor Placement**: Position sensors uniformly and close to each other within the chamber to ensure even exposure to environmental conditions, avoiding walls, vents, and other sources of gradients. Place the sensors near or inside a large heat buffer when evaluating temperature performance.
- **Air Circulation**: Ensure adequate air circulation for homogenous conditions throughout the chamber.
- **Reference Instruments and Data Logging**: Use reliable, high quality, calibrated reference instruments (or regularly calibrated transfer standards) and data logging equipment to accurately record sensor responses.

2.1 Environmental Chamber Recommendations and Setup

The selection of an appropriate environmental chamber is essential for creating stable and reproducible test conditions. For comprehensive RHT sensor evaluation, temperature/humidity-controlled chambers or stability chambers are recommended. These chambers allow for precise control of both temperature and humidity levels, enabling the simulation of a wide range of environmental conditions relevant to the intended sensor applications.

Before starting any tests, thorough calibration and validation of the environmental chamber is recommended. Calibration involves adjusting the chamber's controls to ensure accurate temperature and humidity readings. Validation involves verifying the chamber's performance by comparing its readings to those of trusted reference instruments, such as chilled mirror hygrometers for humidity and precision thermometers for temperature. Calibration and validation should be performed regularly to maintain the accuracy and reliability of the test environment.

The placement of sensors within the chamber significantly impacts the accuracy of the measurements. Sensors should be positioned to ensure uniform exposure to the controlled environmental conditions. Avoid placing sensors near the chamber walls, air vents, or other sources of temperature or humidity gradients. Additionally, adequate air circulation within the chamber is crucial for maintaining homogeneous conditions throughout the test volume. Also, the temperature and humidity distribution within an environmental chamber will never be perfectly uniform. It is common to observe temperature differences of 1.5K and more even for sophisticated chambers, and thus additional variations should be minimized.

2.2 Measurement Instrumentation

Accurate measurement of RH and temperature during sensor evaluation requires the use of reliable and well-calibrated reference instruments. Chilled mirror hygrometers are considered the gold standard for RH measurement, offering high accuracy and excellent stability. Precision thermometers, such as platinum resistance thermometers (PRTs), are recommended for temperature measurement due to their accuracy and linearity across a wide temperature range. Due to the considerable cost and complexity of these reference instruments, it is acceptable to use a regularly calibrated transfer standard like a humidity and temperature probe. The calibration of the transfer standards should be performed by an ISO/IEC 17025 accredited laboratory using calibration standards that are traceable to some national agency, for example the National Institute of Standards and Technology (NIST, USA), Physikalisch-Technische Bundesanstalt (PTB, Germany) or National Physical Laboratory (NPL, UK).

Data logging equipment and software are essential for recording sensor outputs and reference measurements. The data logging system should be capable of capturing data at a sufficient sampling rate to accurately represent the dynamics of the sensor response. Usually, a sampling rate of one sample per second (1Hz) is sufficient for temperature and humidity measurements. Proper connection of sensors to the data acquisition system is crucial to ensure accurate data transmission. Follow the general guidelines for wiring and shielding to minimize noise and interference. Prior to starting any tests, establish a stable baseline by allowing the sensors and reference instruments to equilibrate to the chamber conditions. This ensures that any subsequent changes in sensor output can be attributed to variations in the environmental parameters being tested.

3. Accuracy Testing Methodologies

3.1 General Testing Guidelines

Each Renesas HSx series sensor undergoes individual calibration before shipment, utilizing:

- Precision equipment for controlling relative humidity and temperature.
- High-accuracy RH and temperature references, traceable to national standards (for example, NIST in the USA) and periodically calibrated by an ISO/IEC 17025 accredited laboratory.

To ensure accurate testing and maintain the quality of your results, follow these guidelines:

1. **Sensor Handling**: Always use sensors from their original packaging to avoid contamination or damage.
2. **Sample Size**: Test a sample size of minimum 5 (preferred 10) sensors to obtain statistically significant results.
3. **Soldering Guidelines**: If soldering sensors onto PCBs is necessary, follow proper soldering techniques to prevent damage (see "Soldering Information" found in the datasheet for detailed instructions on soldering).
4. **Rehydration**: After soldering, rehydrate sensors by exposing them to 75% RH at room temperature (20°C to 30°C) for at least 12 hours, or 40% to 60% RH for 5 days. This step is crucial to restore the sensor's moisture equilibrium.
5. **Sensor Conditioning**: In case of unknown storage conditions and history of the sensors, follow a two-step conditioning process:
    a. Bake the sensors at ~100°C with humidity < 10% RH for 10 to 12 hours.
    b. Rehydrate the sensors as described in step 4.

6. **Reference Instruments**: Use a high-quality, recently calibrated reference (for example, a calibrated RH probe or chilled mirror hygrometer and a platinum resistance thermometer) for comparison.
7. **Test Environment**: Ensure that both the reference instrument and the device under test (DUT) experience the same RH and temperature conditions. Utilize a professional humidity chamber or a closed, inert box (for example, stainless steel) to create a stable and uniform environment. Minimize the distance between test sensors and the reference device. A heavy metal housing or similar heat buffer is essential for accurately measuring sensor temperature performance.
8. **Stabilization Time**: Allow at least 45 minutes for RH conditions to stabilize within the test enclosure before taking measurements. Additional time may be needed for the first data point or after temperature changes to reach a thermal equilibrium. The stabilization time can significantly increase when using a heat buffer for optimal temperature accuracy. This depends on the buffer's heat capacity and can take up to 10 hours for large temperature differences.
9. **Measurement Frequency and Averaging**: Measure at a frequency of 1 measurement per second and average 10 measurements at each point to account for potential noise in the chamber's conditions.
10. **Record RH and Temperature**: Always record both relative humidity and temperature data for all measurements, as RH readings are temperature dependent. This helps identify potential sources of error.

3.2 Testing Relative Humidity Accuracy

To assess the relative humidity (RH) accuracy of Renesas HSx polymer-based capacitive sensors, follow this recommended test profile:

- **Temperature**: Maintain a constant temperature of 25°C throughout the test.
- **RH Points**: Test at least three humidity levels: 20% RH, 50% RH, and 80% RH.
- **Stabilization Time**: Allow at least 45 minutes for stabilization at each RH point before taking measurements.

This profile can be executed in both ascending and descending order of humidity levels to evaluate sensor hysteresis. Hysteresis is the difference in sensor output when the same RH level is approached from a higher or lower value.

Example: The example measurements in this document use a custom test PCB that can hold up to 56 HSx sensors per board (see Figure 1 and Figure 2). These boards are designed to minimize the heat impact of components on the HSx sensors. Multiplexers (MUX) are used to communicate with each individual sensor.

Figure 1. Example PCB for HSx Testing

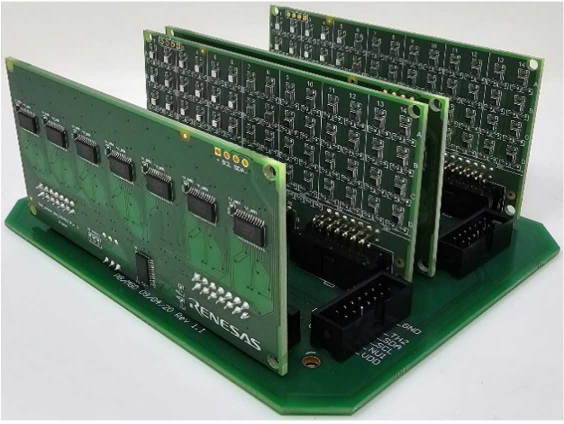

Figure 2. Example Setup with 4 HSx PCBs Connected

In this measurement, an extended RH range from 10% to 95% was used. The temperature was maintained at a constant 25°C. Figure 3 shows the setup within the environmental chamber (Binder MKF 56). The reference is placed as close as possible to the devices under test. The reference device used in this example is a recently calibrated Vaisala HMT314 RHT Probe with a typical accuracy of ±1% RH (0 to 90 %RH) and ±1.7% RH (90 to 100% RH).

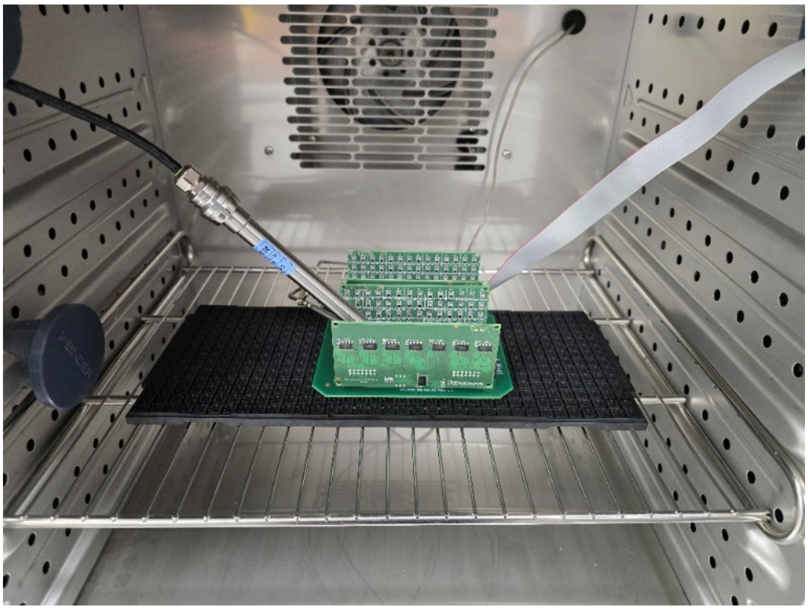

Figure 3. Example Test Setup in an Environmental Chamber

Results of 220 HS4001 sensors are presented in Figure 4. The upper plots display the full sensor data of the HSx sensors (colored lines) as well as the reference sensor (black line). Below, the violin plot shows the distribution of the HSx RH error against the reference sensor. The stable data used for the violin plot is highlighted in the full sensor data plot and confirms that only stable conditions must be considered for analysis.

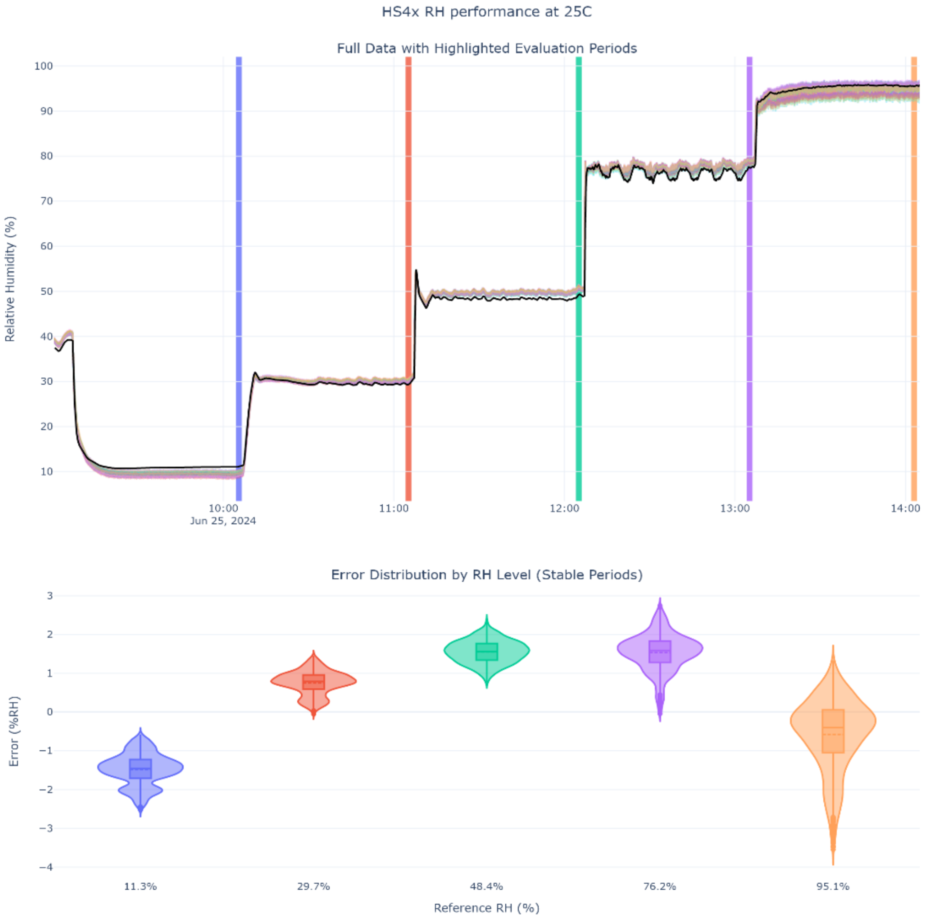

Figure 4. RH Performance Measurement Results

3.3 Testing Temperature Accuracy

The general guidelines for testing relative humidity accuracy also apply to temperature accuracy testing. Ensure a high-accuracy reference thermometer is used. In addition, ensure that both the reference and sensor under test are exposed to the same temperature.

A heavy metal housing or similar heat buffer is essential for accurately measuring sensor temperature performance. Temperature changes typically take longer to stabilize than humidity changes, often requiring at least 60 minutes after each temperature adjustment. However, the exact stabilization time depends on the specific setup, including the size and weight of the items being tested and the environmental chamber used.

3.3.1 Recommended Temperature Profile

- **Temperature Points**: Test at least three different temperature points like 5°C, 25°C, and 45°C.
- **Stabilization Time**: Allow minimum 60 minutes for stabilization at each temperature point before taking measurements.

Example: The same HSx test PCBs including 112 HS4001 sensors as described in section 3.2 was utilized and positioned within a robust aluminum chamber to guarantee consistent temperature and stability across all sensors (see Figure 5 and Figure 6). An extended temperature range to demonstrate the performance of HSx sensors from -40°C to 100°C was used. The reference device in this test was a calibrated Vaisala TMP1 temperature probe with a typical accuracy of less than 0.1°C throughout the entire temperature range. The initial temperature of -40°C was maintained for 10 hours to ensure stability and allow sufficient time for temperature settling. All following temperature levels were held for 5 hours.

Figure 5. Example of a Heat Buffering Housing for Temperature Accuracy Tests

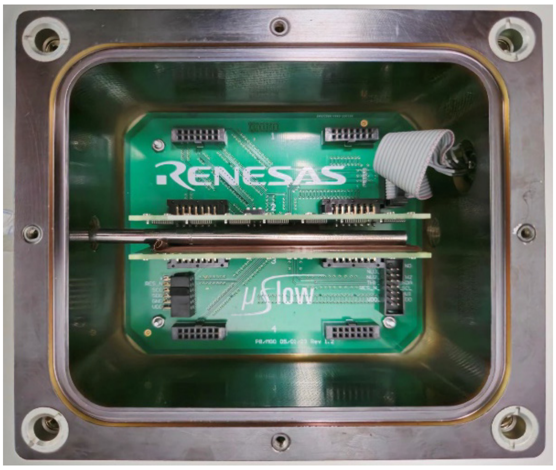

Figure 6. Example Setup for Temperature Accuracy Test with Reference and Test PCBs

The measurement results are presented in Figure 7. The upper plots display the full sensor data of the HSx sensors (colored lines) as well as the reference sensor (black line). The violin plot shows the distribution of the HSx temperature error against the reference sensor. The stable data used for the violin plot is highlighted in the full sensor data plot and confirms that only stable conditions must be considered for analysis.

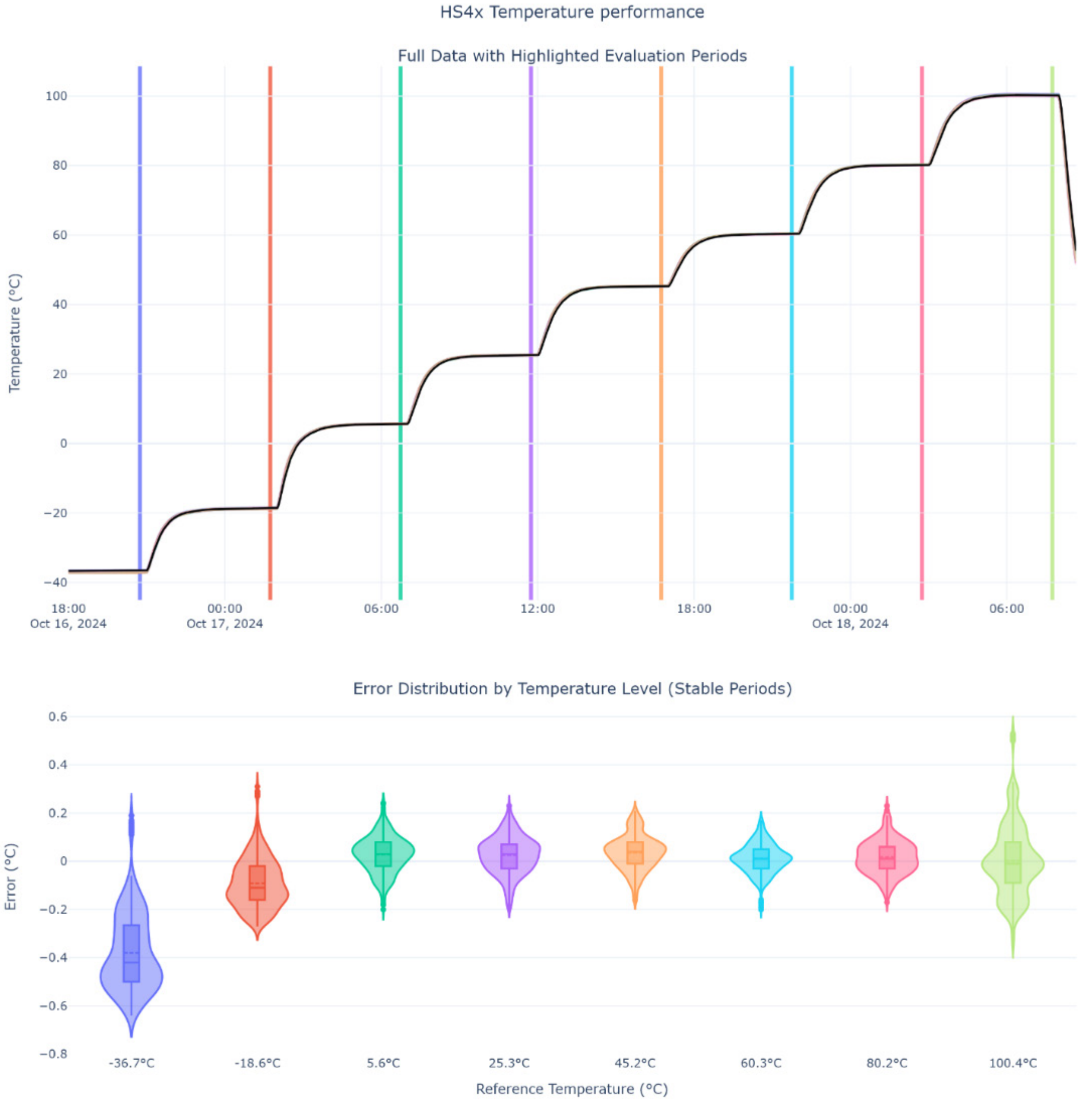

Figure 7. Temperature Performance Measurement Results

Observe the difference in measurement results when no metal housing (heat buffer) was used (see Figure 8) and the devices were operated in an open chamber similar to that shown in Figure 3. The device-to-device deviation is significantly higher, even though the same sensors were employed in this test. These results might suggest malfunctioning sensors; however, the performance is within specifications when tested correctly.

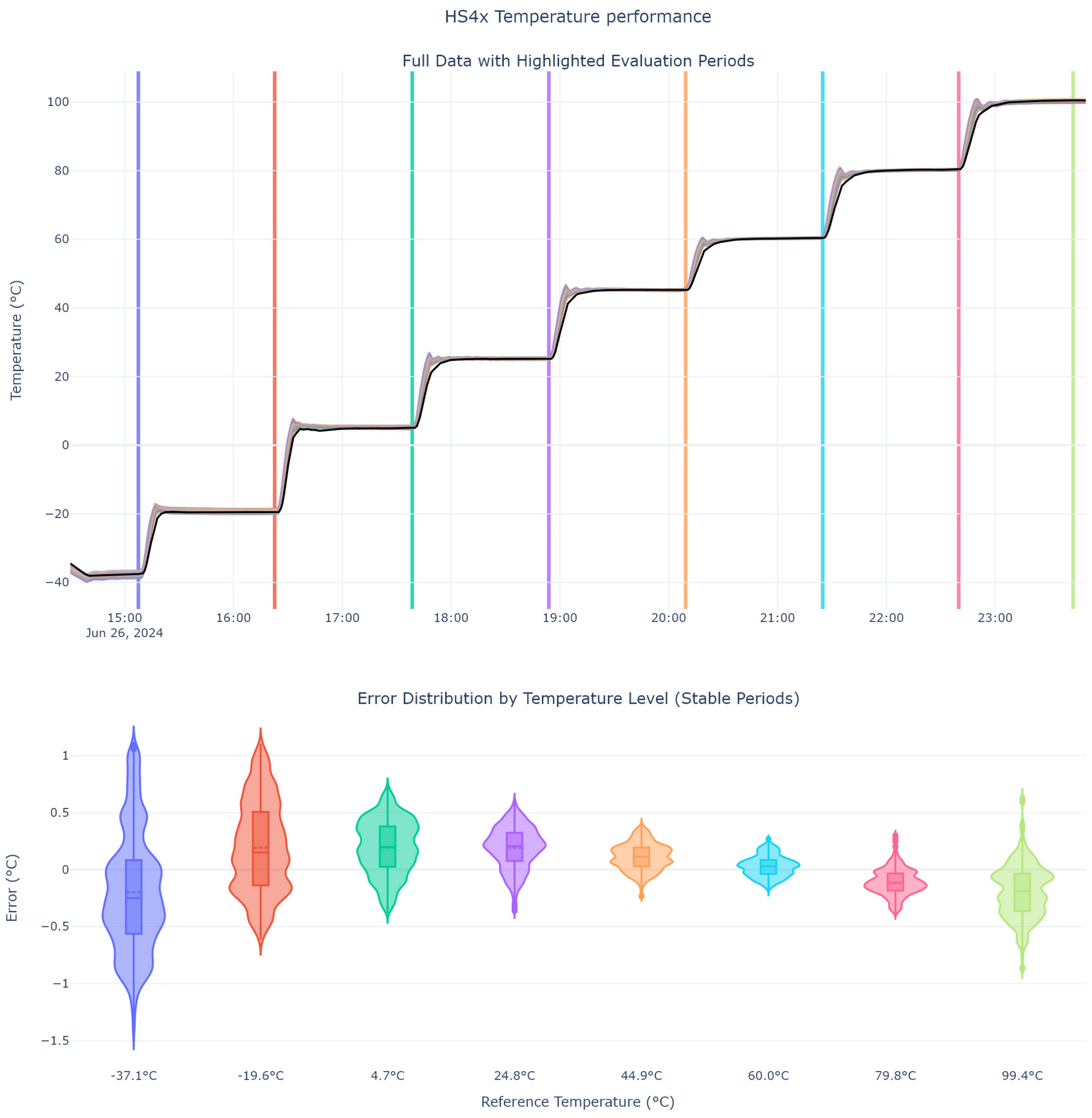

Figure 8. Example of Measurement with Low Temperature Uniformity

4. Best Practices for Evaluating Sensor Performance

Evaluating the performance of sensors is a critical step in ensuring accuracy and reliability in various applications. Proper evaluation involves comparing the sensor readings with a high-accuracy reference and understanding the metrics that can quantify the sensor's performance. The following sub-sections offer some hints and guidelines for effectively evaluating sensor performance.

4.1 Use Stabilized Data

To achieve accurate performance evaluation, it is crucial to use only the data that has been sufficiently stabilized. As discussed throughout section 3, temperature and humidity changes require time to stabilize. Ensure to allow adequate stabilization time at each measurement point before collecting data. For example, a minimum of 60 minutes should be allowed for temperature stabilization, though this may vary depending on your specific setup.

4.2 Metrics for Performance Evaluation

When evaluating sensor performance, several metrics can be used to quantify the accuracy and precision of the sensor. Two commonly used metrics are Root Mean Square Error (RMSE) and Mean Error.

4.2.1 Root Mean Square Error (RMSE)

RMSE is a measure of the differences (spread) between the values predicted by the sensor and the actual values from the reference device. It provides a single number that sums up the overall prediction error of the sensor. The formula for RMSE is:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - A_i)^2}$$

where (P_i) is the measured value from the sensor, (A_i) is the actual value from the reference device, and (n) is the number of measurements.

A lower RMSE value indicates a better-performing sensor.

4.2.2 Mean Error

Mean Error is another relevant metric that indicates the average error of the sensor readings compared to the reference device and is calculated as:

$$\text{Mean Error} = \frac{1}{n}\sum_{i=1}^{n}(P_i - A_i)$$

where (P_i) is the predicted value from the sensor, (A_i) is the actual value from the reference device, and (n) is the number of measurements.

A mean error close to zero indicates that, on average, the sensor readings are very close to the reference values.

4.3 Example of Data Analysis

Consider that you have collected stabilized data from your sensor and the reference device. Here is how you can calculate and interpret RMSE and Mean Error:

1. **Collect Data**: Ensure data has been collected after sufficient stabilization time.
2. **Compute RMSE and Mean Error**: Use the formulas provided to compute RMSE and Mean Error from the collected data. Only use data where humidity or temperature changes have stabilized.
3. **Analyze Results**: Compare the RMSE and Mean Error values to determine the sensor's performance.

Table 1 displays test data as it relates to the measurement of relative humidity. The reference device used in this example is a recently calibrated Vaisala HMT314 RHT Probe with a typical accuracy of ±1% RH (0 to 90 %RH) and ±1.7% RH (90 to 100% RH).

Table 1. Results for RH Accuracy Test Data Analysis

Relative Humidity Level in % RH	RMSE in % RH	Mean Error in % RH	Datasheet Specification (typ.) in ±% RH
10	1.5	-1.5	1.5
30	0.725	0.7	1.5
50	1.6	1.6	1.5
75	1.6	1.6	1.5
95	1.1	-0.9	2.0

4.4 Additional Considerations

- **Environmental Conditions**: Always consider the environmental conditions during testing. Fluctuations in temperature, humidity, and other factors can affect sensor performance.
- **Repeatability**: Conduct multiple tests to ensure repeatability and reliability of the sensor readings.
- **Calibration**: Regularly calibrate both the sensor and the reference device to maintain accuracy.

By following these tips and using metrics like RMSE and Mean Error, sensor performance is effectively evaluated to ensure they meet the required accuracy standards.

5. Troubleshooting

In the process of evaluating and utilizing temperature and humidity sensors, users may encounter some common issues that may affect the accuracy and reliability of their measurements. The following sections describes some of these common issues, along with practical tips and solutions.

5.1 Temperature Offset Due to PCB Heating

Issue:

Temperature sensors can exhibit an offset in readings due to the heating of the printed circuit board (PCB). This issue is particularly prevalent in densely populated PCBs where heat generation from other components can affect the sensor.

Solution:

- **Isolate the sensor**: Place the temperature sensor away from heat-generating components. Use thermal barriers or shields to minimize heat transfer. As a practical example, cutouts in the PCB around the HSx sensor should be implemented and solid metal planes such as copper should be avoided in the vicinity of the sensor since these will act as thermal conductors. Follow the PCB layout guide provided in the datasheet for additional tips.
- **Active cooling**: Implement active cooling solutions like fans or heatsinks to dissipate excess heat of high-power components.
- **Compensation calculations**: Use the compensation equations to factor in the temperature influence of other components on the temperature measurements. For more information, see the application note Compensating Temperature and Relative Humidity for a PCB.

5.2 Temperature Deviations Due to Uneven Temperature Distribution in the Chamber

Issue:

Uneven temperature distribution within the testing chamber can lead to inaccurate temperature readings. High deviations between sensors can often be observed when they are not placed inside or near a large heat buffer.

Solution:

- **Improve airflow**: Ensure proper ventilation within the chamber. Use fans to circulate air and achieve uniform temperature distribution.
- **Chamber design**: Insulate and optimize the design of the chamber to promote a uniform temperature distribution.
- **Sensor placement**: Position the sensors at multiple points within the chamber to monitor and adjust for any temperature gradients. Place sensors inside or near a large heat buffer to improve temperature distribution and stability.

5.3 RH Offset Due to Polymer Moisture Variations

Issue:

Relative Humidity (RH) sensors utilize hygroscopic polymers that can become dehydrated or saturated, leading to offset in RH readings. Dehydration may occur in low humidity environments, while saturation can result from exposure to high humidity. A negative RH offset means the sensor is dehydrated, while a positive RH offset indicates polymer saturation.

Solution:

- **Conditioning**: Follow the datasheet instructions to condition the RH sensors by exposing them to a controlled humidity environment to properly rehydrate the sensing polymer.
- **Environmental Control**: Avoid extreme humidity conditions to prevent polymer dehydration or saturation. This includes high temperatures (>60°C) with high humidity (>90% RH) or low humidity (<10% RH), and condensation events. Use desiccants or humidity control equipment as needed.

6. Revision History

Revision	Date	Description
1.00	Jan 14, 2025	Initial release.

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