Application Note

Humidity Sensor-Based Water Ingress Monitoring for Automotive Electronics

Alex Thompson, Sakeenah Khan, Carolus Andrews *Temperature & Humidity Sensing*

ABSTRACT

Water ingress or intrusions can be a significant threat to critical electronic components used in many applications, including automotive and enterprise systems such as electric power steering (EPS), EV battery packs, LiDAR and liquid-cooled servers. This application note presents a humidity sensor-based detection method utilizing the HDC3020 sensor to rapidly identify water ingress in sealed or vented electronic enclosures, using the slew rate (for example, rate of change) of relative humidity (RH) as an indicator for water ingress events. Specifically, the RH slew rate can be calculated over a 10-second window and compared against a threshold to detect when a water ingress event occurs. This approach reliably detects even minor leak events (≤0.07mL in a 1.7L enclosure) within seconds. This outperforms conventional PCB-trace electrode water sensors, enhancing system reliability, reducing false positives, and simplifying sensor deployment.

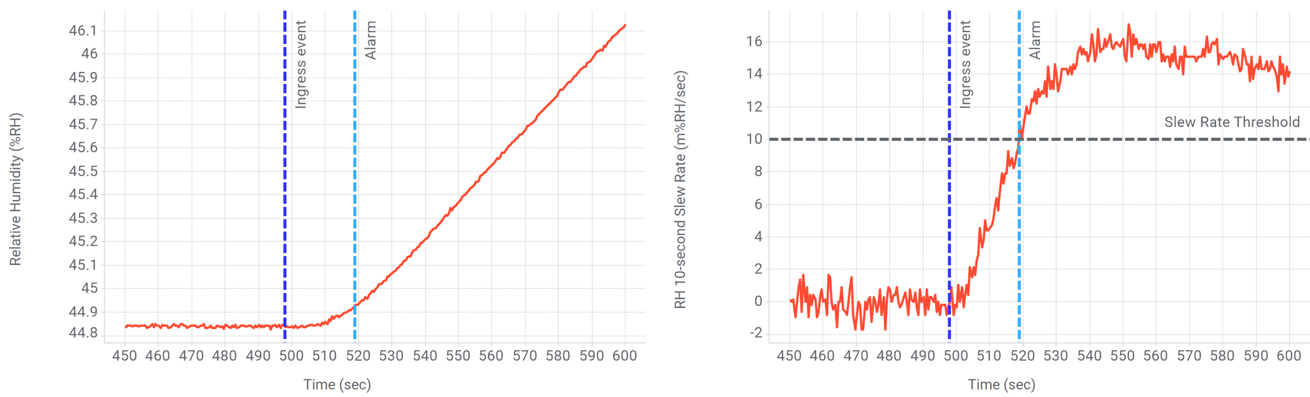

Figure 1-1. Water Ingress Detection Using RH Slew Rate Threshold

Table of Contents

Trademarks

All trademarks are the property of their respective owners.

1 Introduction

1.1 Motivation

Established technologies are being challenged by new demands for greater efficiency and performance. For example, electric vehicles (EVs) have surged in popularity over the past decade, and given that EVs generally use more electronics, this increases the number of systems that can be exposed to water ingress risks. Similarly, data centers are expanding rapidly as storage and computing workloads move to the cloud, requiring higher performance and intensive cooling. These trends introduce new engineering challenges – including a greater reliance on liquid cooling – which in turn raises the risk of water leaks in electronic systems.

Electric power steering (EPS) is one example of a subsystem evolving with these trends. While hydraulic power steering is still used, EPS offers greater efficiency by running the assist motor only on demand instead of continuously. Initially, EPS motors were placed inside the vehicle cabin (on the steering column) to keep them protected, but this configuration left drivers feeling less connected to the road compared to hydraulic systems. The design was updated to move the EPS motor to the wheelbase to improve steering feel. However, placing the motor and the control electronics near the wheel exposes them to the environment. Worn dust boots or failing seals can allow water to penetrate the system, ultimately introducing one of the worst enemies of electronics: water ingress.

1.2 The Physics of Humidity and Water Ingress

In general, the main objective for water ingress applications is to reliably detect and notify of the presence of water inside an enclosure. Taking this into consideration, some end applications can require the ability to distinguish between water ingress and condensation. For the purposes of this investigation, the assumption is that any water in the enclosure can be deemed problematic, and is therefore treated as water ingress. Without an external disturbance to drive a specific factor, changes to temperature or RH typically occur slowly over longer periods of time. As such, testing windows when measuring temperature or RH are typically larger than for most electronics algorithms, with windows extending as high as 60 to 120 seconds in application.

Relative humidity is the most common humidity measure. This is defined as the percentage of water vapor present in air relative to the maximum capacity at that temperature. This essentially measures: How full of water is the air? At 100% RH, the air is fully saturated – any additional moisture can condense into liquid water. Mathematically, RH quantifies how far the existing partial pressure of water vapor is from the saturation vapor pressure at the same temperature and pressure, as shown in Equation 1.

$$RH = \varphi = \frac{WaterVaporContent}{Max.WaterVaporCapacity} \equiv \frac{CondensationRate}{EvaporationRate} \equiv \frac{ActualVaporPressure}{SaturationVaporPressure} \quad (1)$$

RH is highly temperature-dependent – if temperature rises, RH falls (for the same absolute moisture content), and if temperature falls, RH rises. This is because as temperature increases, the saturation vapor pressure of the air increases as well while the actual vapor pressure remains constant (assuming no new moisture has been introduced). This behavior complicates a simple humidity threshold for leak detection. Given enough time, a vented enclosure's humidity can slowly climb to a high RH just from ambient conditions, potentially triggering a false alarm if only relying on an absolute RH level. However, such gradual changes happen very slowly, so focusing on the slew rate (or rate of change) of humidity can filter them out.

Absolute humidity (AH) alone is not a reliable water ingress indicator in a vented system. AH is not affected by temperature explicitly – this is just an amount per volume. However, because volume can change with temperature and pressure, AH of an air parcel can vary even if no water is added or removed. If air expands (for example, rising to high altitude where pressure is lower), the AH decreases (the same water molecules now occupy a larger volume). Vents can help with pressure equalization, but if an unvented closed container is cooled, the air contracts a bit and AH increases slightly; more significantly, some vapor can condense, which reduces the AH (because those molecules leave the gas phase).

Evaporation is the process of liquid water turning into water vapor through a state change. Typically, the liquid-to-vapor phase change is assumed to be the boiling point of water. However, evaporation occurs at any temperature with sufficient energy for molecules on the water’s surface. When water leaks occur, the liquid water can immediately begin evaporating. The evaporation can occur at different rates depending on the temperature of the system and volume of water. This new introduction of water vapor into the air is detected as a change in RH by the humidity sensor IC. Evaporation can differ based on the ambient humidity in the system. If the air is drier (low RH), then the rate of evaporation can increase. If the air is already humid (high RH), the rate of evaporation can decrease. This is relevant since water ingress can occur at different temperature and humidity conditions, so this can affect how the RH changes in the system over time.

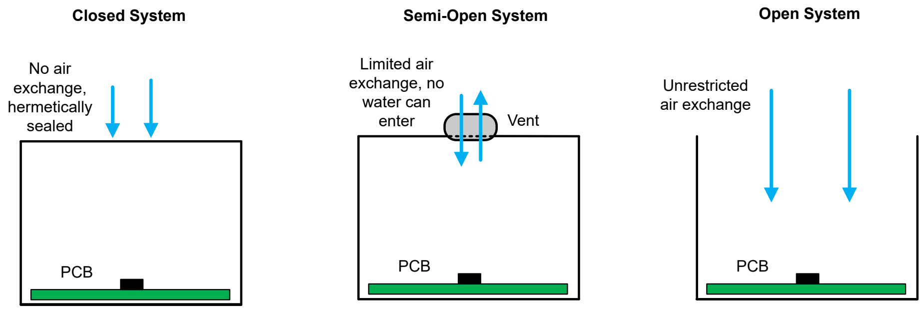

Figure 1-1. Closed, Semi-Open, and Open Systems

A condition that was not evaluated during this experiment was an open system. The test enclosure described in the following was a semi-open system, and the results apply to a fully closed system as well. An open system means the electronics are completely exposed to the air and potentially water. For example, an open system with water ingress concerns can be a liquid cooled server. The server and the electronics have a free and uncontrolled air exchange with the environment, but the liquid is held within tubes and needs to be monitored for leaks. A closed system is one where there is no exchange of air inside and outside of the system. Hermetically sealed systems are closed systems. A semi-open system is one where there is some controlled and limited air exchange with the outside environment through a filtered vent or permeable membrane. By using the protective vent on the test setup, this application note covers how to detect water leaks in semi-open systems (findings can apply to closed systems as well). Open systems are more susceptible to large swings and RH levels in the ambient air, which can complicate using a rate of change threshold to detect water ingress.

2 Test Methodology

A custom test enclosure was designed to evaluate water ingress detection under realistic conditions. The enclosure was built to be robust across a range of temperatures and humidity levels, flexible enough for various test scenarios, and representative of a typical vented electronics housing.

One additional scenario was evaluated before the main experiment with the sensor outside of the enclosure, where a water droplet was placed directly on the HDC3020 sensor cavity. In such a case, the sensor reading momentarily drops to 0%RH for a few seconds, then rises above the original value until the water evaporates or is removed (after which normal readings resume). The drop to 0%RH is nearly instantaneous. This distinctive signature unambiguously indicates water reaching the sensor cavity, independent of the variables tested within this study such as ambient conditions, enclosure type or size, water volume, and so forth. In cases where liquid water is expected and such behavior must be avoided, an alternative device option is the HDC3022, which comes with a waterproof IP67 rated filter.

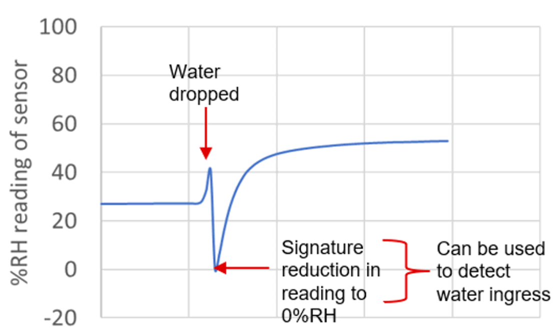

Figure 2-1. HDC3020 %RH Response When a Water Droplet is Placed Directly Into Sensor Cavity

The test enclosure was used to emulate a semi-open system with a waterproof vent at the top to allow air exchange. The vent served two purposes: this mimicked real-world enclosures (which are rarely hermetically sealed) and this prevented pressure buildup during testing when conditioned air was pumped in. Without the vent, introducing humid or dry air from an external chamber can over-pressurize the box. The additional pressure can change the AH in a way other than water entering the system.

Inside the enclosure, a test PCB held the HDC3020 sensor, which was mounted on a small raised board so this cannot be submerged by any incoming water. Water was introduced through a funnel, simulating either a slow drip or a rapid pour. A heatsink and heater were added next to the PCB to vary the temperature inside the enclosure. This allowed the box to be heated to elevated temperatures without needing to place the entire enclosure inside of a heated environmental chamber. Humid and dry air was supplied through a pneumatic tube connection to a humidity chamber directly into the test enclosure.

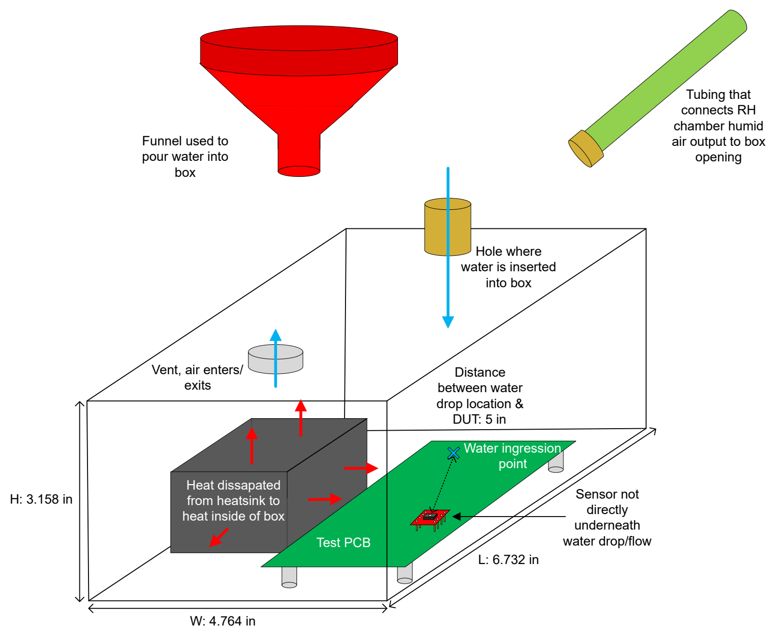

Figure 2-2. Vented Test Enclosure With Internal and External Components

Testing was performed under a variety of ambient conditions to make sure the detection algorithm works across the range of scenarios in which water ingress can occur. In automotive and industrial applications, leaks can happen in cold and dry climates as well as hot and humid ones. Accordingly, the system was evaluated at several representative conditions.

Table 2-1. Summary of Experimental Trials

Test Number	Temperature (°C)	Relative Humidity (%RH)	Amount of Water	How was Test Performed?
1	22°C	45-50%	One drop of Water (0.023mL)	Indoor ambient conditions, no forced humid air
2	22°C	45-50%	Three drops of Water (0.07mL)	Indoor ambient conditions, no forced humid air
3	22°C	45-50%	Full Water Flow (100mL)	Indoor ambient conditions, no forced humid air
4	22°C	70%	Full Water Flow (100mL)	Indoor ambient conditions, humid air forced
5	50°C	10%	Three drops of Water (0.07mL)	Enclosure heated internally, dry air forced
6	50°C	70%	Three drops of Water (0.07mL)	Enclosure placed directly in humidity chamber
7	10°C	10%	Three drops of Water (0.07mL)	Enclosure cooled in ice bath, dry air forced
8	10°C	70%	Three drops of Water (0.07mL)	Enclosure cooled in ice bath, humid air forced

One drop of water was measured to be approximately 0.023mL, while three drops of water was approximately 0.07mL. For the drop tests, after acclimating the box to the set humidity level, the humid air tube was removed and water was deposited into the enclosure through the brass fitting hole with a dropper. For *full flow* (100mL) of water tests, a funnel was used to pour the water into the same fitting hole. After water was deposited into the enclosure, the brass fitting hole where the humid air can be piped in was closed, to prevent the evaporating water and humid or dry air from escaping.

All test conditions were evaluated with three drops of water to simulate a minor water leak. The "full flow of water" tests were designed to simulate a much larger volume of water breaking into the system. The overtemperature tests were not done with the larger volume of water, because pouring lots of water into the enclosure requires extensive clean up between tests and often requires a disassemble of the test enclosure. Furthermore, using a smaller volume of water is the worst-case test for the humidity sensors to detect because much less water vapor can be evaporated into the air, representing a stronger test of the proposed RH slew rate threshold method. Lastly, a one-drop test was performed for test 1 to push the boundaries on how fine of an Ingres event the HDC3020 can reliably detect at the given test enclosure size.

3 Assumptions

For this water leak detection experiment, a few assumptions were made to narrow the scope of the testing:

- **A vent was incorporated in the enclosure for pressure equalization.** This prevents pressure buildup as internal temperature changes. In the experiment, TI used a waterproof vent to allow dampened air exchange with the atmosphere, allowing for pressure equalization while blocking liquid water. While this constitutes a semi-open system, this assumption still allows the experimental results to apply to closed systems. Nominally sealed systems do not develop internal pressure. Even a closed system that was hermetically sealed at atmospheric pressure, when punctured during a leak event, does not see a pressure change occur.
- **The system is started in a dry, known-good state at the beginning of each test.** The assumption is that no water is present in the enclosure at time zero of the algorithm. The tested enclosure was completely dry at the start of every experiment trial. Determining if a system was already wet before startup is outside the explicit scope of these tests. Water ingress is a single event.
- **Temperature is held constant during each test.** TI assumes no significant heating or cooling occurs while a leak event is in progress. For the high- and low-temperature tests, the water was previously conditioned to the target temperature to avoid introducing any temperature-change effects on humidity.

4 Proposed Algorithm Using Slew Rate Threshold

The proposed method to detect a water ingress event uses a threshold for the slew rate of the RH measurement. The humidity sensor needs to be set to measure RH at a rate of 1-2 samples per second (1-2Hz). Then, the slew rate needs to be calculated over a 10 second window. To compute the 10-second RH slew rate, first ΔRH is obtained by taking the difference between the current RH measurement (RH_N) and the measurement from 10 seconds ago (RH_{N-10}). Then, ΔRH is divided by Δtime and multiplied by 1000 to yield the slew rate in units of m%RH/s (milli-percent RH per second), as shown in Equation 2.

$$RH \quad Slew\ Rate\left(\frac{m\%RH}{sec}\right) = \frac{\Delta RH}{\Delta time} = \frac{1000 \times \left(RH_N - RH_N - 10\right)}{10\ sec} \tag{2}$$

This calculation can be made in software, and has a memory requirement of storing RH measurements from the last 10 seconds within a data buffer, such as a FIFO (first-in first-out) buffer. Figure 4-1 shows the proposed algorithm as a the flow chart. The slew rate threshold method was tested across various temperature and humidity conditions, given a steady-state temperature and pressure (as outlined in the Assumptions section).

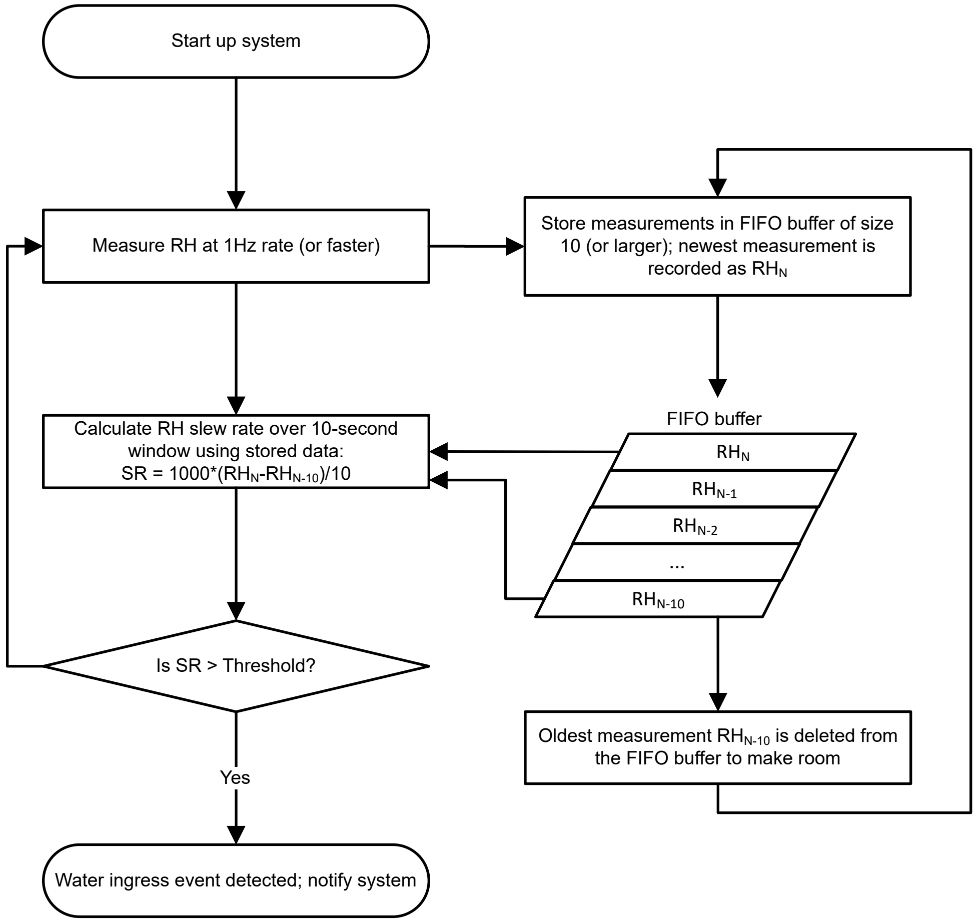

Figure 4-1. Water Ingress Detection Algorithm Flowchart

A slew rate threshold needs to be set in the software to alarm when the measured slew rate exceeds the threshold, indicating a water ingress event has occurred. The designed for slew rate threshold depends on factors such as the enclosure size and the required sensitivity (volume of water that must be detected). Based on the data collected, 10m%RH/s was identified as the designed for threshold to reliably detect an ingress event of ≤0.07mL in the given 1.7L enclosure. Tests across various conditions showed that leak events of 0.07mL or more produced a rapid rise in RH well above the chosen threshold, whereas normal ambient humidity fluctuations stayed below the threshold. Similar test procedures can be followed to characterize an appropriate threshold for different system enclosures.

Figure 4-2 shows how the slew rate threshold can be used to detect a 0.07mL water ingress event using data collected for test #2 (22°C, 45%RH, 0.07mL water). The vertical dark blue line marks the ingress event (when water was introduced into the test system), the horizontal black line marks the proposed 10m%RH/s slew rate threshold, and the vertical light blue line marks the ingress alarm event (when the threshold was exceeded). The next section contains the detailed test results and data analysis across the multiple tested conditions.

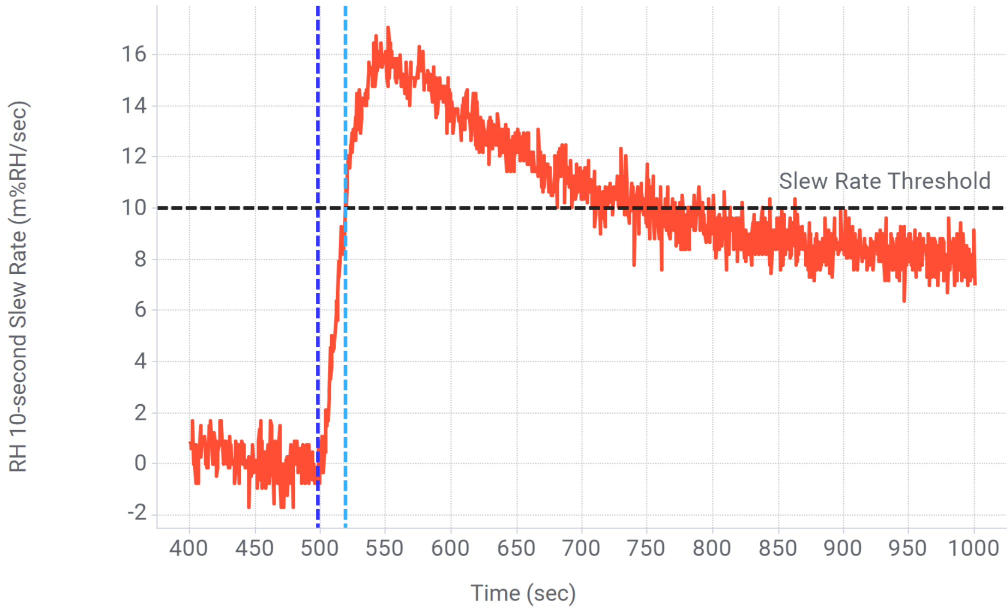

Figure 4-2. Test 2 (22°C, 45%RH, 0.07mL water): RH 10-second Slew Rate vs. Time

5 Test Results

The HDC3020 humidity sensor's response to water ingress was tested across various steady-state conditions, including different ambient temperatures, ambient humidity levels, and amounts of water. The test results confirmed that RH increased when the water ingress occurred, and the RH increase was more pronounced in dry conditions and for larger volumes of water. Thorough data analysis revealed that the most reliable way to detect an ingress event for the given vented test enclosure is to look at the RH slew rate over a 10-second window.

5.1 Test Results at Indoor Ambient Conditions

For tests 1-3 (22°C, 45-50%RH), multiple data points were analyzed, including relative humidity, absolute humidity, dew point, RH slew rate, and AH slew rate, across varied time windows of 1, 5, and 10 seconds. Absolute humidity and dew point were calculated using the following equations, where AH is the absolute humidity (in g/m^3), T_d is the dew point (in °C), RH is the HDC3020 relative humidity measurement (in %RH), and T is the HDC3020 temperature measurement (in °C). The equations are derived from the designed for gas equation and Magnus-Tetens formula, using values approximated by Alduchov and Eskridge (1996).

$$AH\left(\frac{g}{m^3}\right) = \frac{6.11 \times e^{\left(\frac{17.625 \times T}{243.04 + T}\right)} \times RH \times 2.1674}{273.15 + T} \quad (3)$$

$$T_d\left(°C\right) = \frac{243.04 \times \left[\ln\left(\frac{RH}{100}\right) + \frac{17.625 \times T}{243.04 + T}\right]}{17.625 - \ln\left(\frac{RH}{100}\right) - \frac{17.625 \times T}{243.04 + T}} \quad (4)$$

Data analysis showed that merely observing the RH, AH, or T_d does not offer as clear an indicator of a water ingress event as the RH slew rate does. Moreover, placing fixed thresholds on RH or AH for a semi-open system can cause false alarms, since ambient humidity fluctuations can also increase RH over time. Figure 5-1 and Figure 5-2 show the RH, AH, and T_d over time for test 2 (22°C, 45%RH, 0.07mL water).

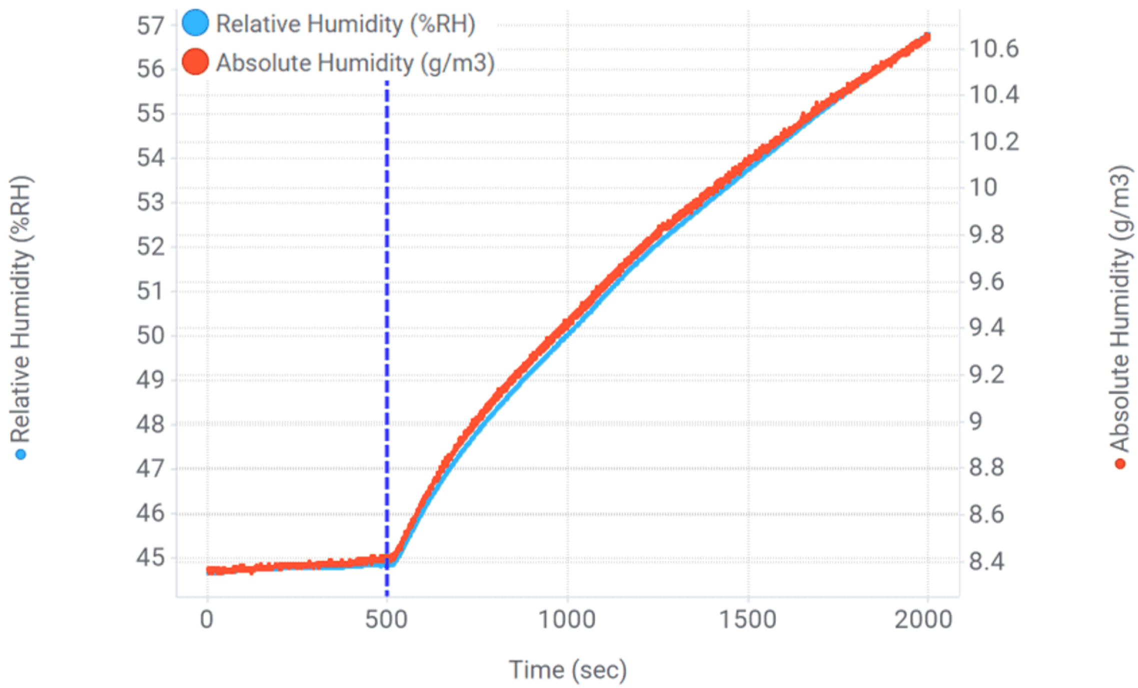

Figure 5-1. Test 2 (22°C, 45%RH, 0.07mL water): Relative Humidity and Absolute Humidity vs. Time

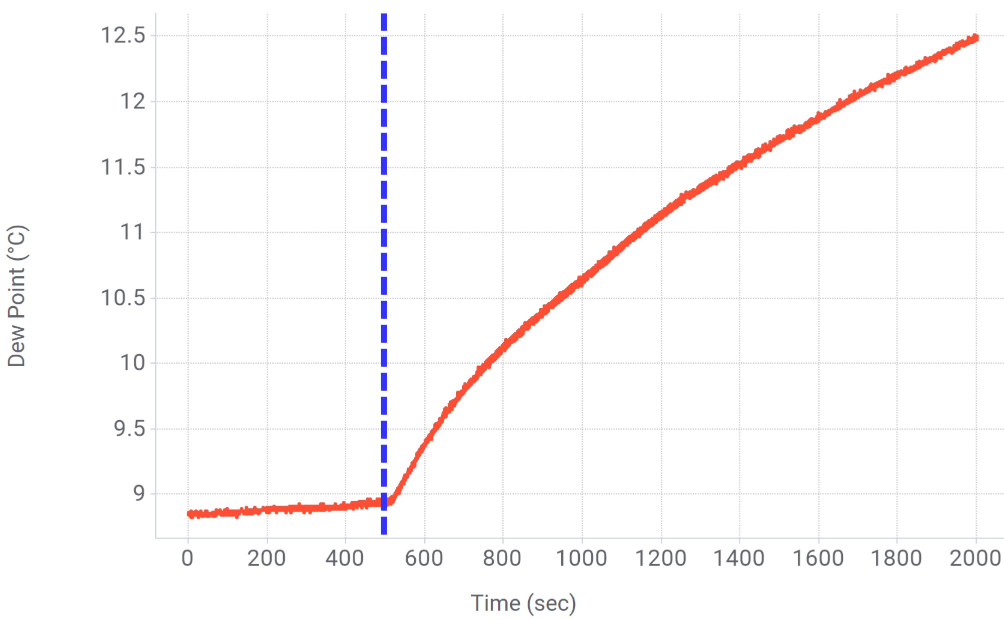

Figure 5-2. Test 2 (22°C, 45%RH, 0.07mL Water): Dew Point vs. Time

The best indicator for the ingress event, especially for smaller volumes of water, was the RH 10-second slew rate. This is because the RH slew rate quickly and dramatically increases upon the introduction of water to the system, as shown in Figure 5-3. The AH slew rate data is too noisy to effectively and reliably indicate an ingress event, as shown in Figure 5-4. In addition, this is better to use a 5 or 10 second window. Slew rate calculations across a smaller time window are dominated by noise, making this difficult to distinguish a true water ingress event, as illustrated in Figure 5-3 and Figure 5-4. Using a 10-second window allows to eliminate noise effects and distinguish the water ingress event from normal humidity fluctuations.

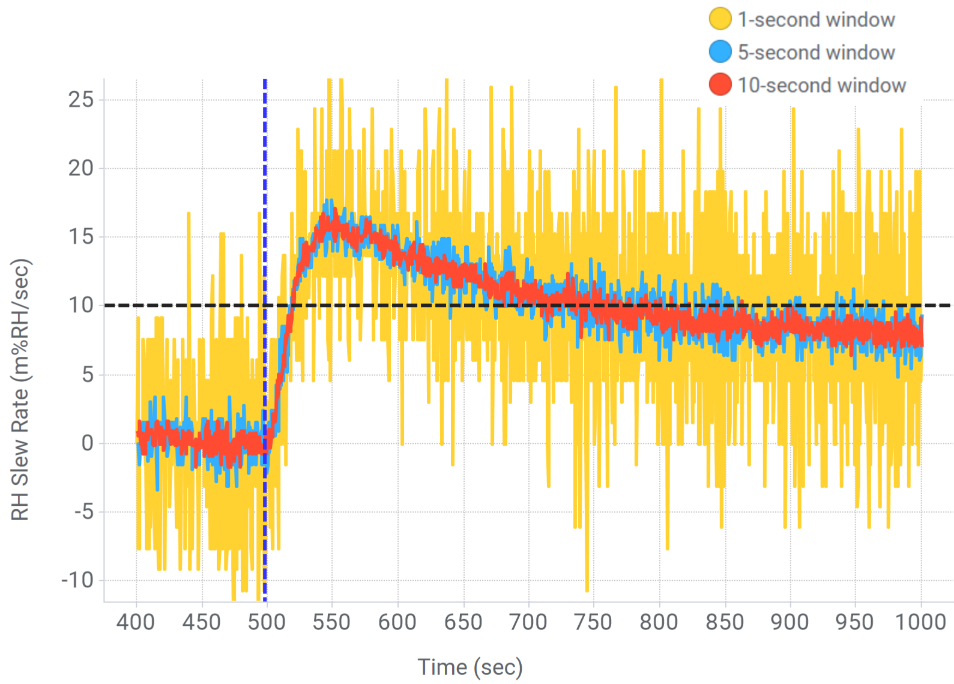

Figure 5-3. Test 2 (22°C, 45%RH, 0.07mL water): RH Slew Rate Calculated Across Different Time Windows

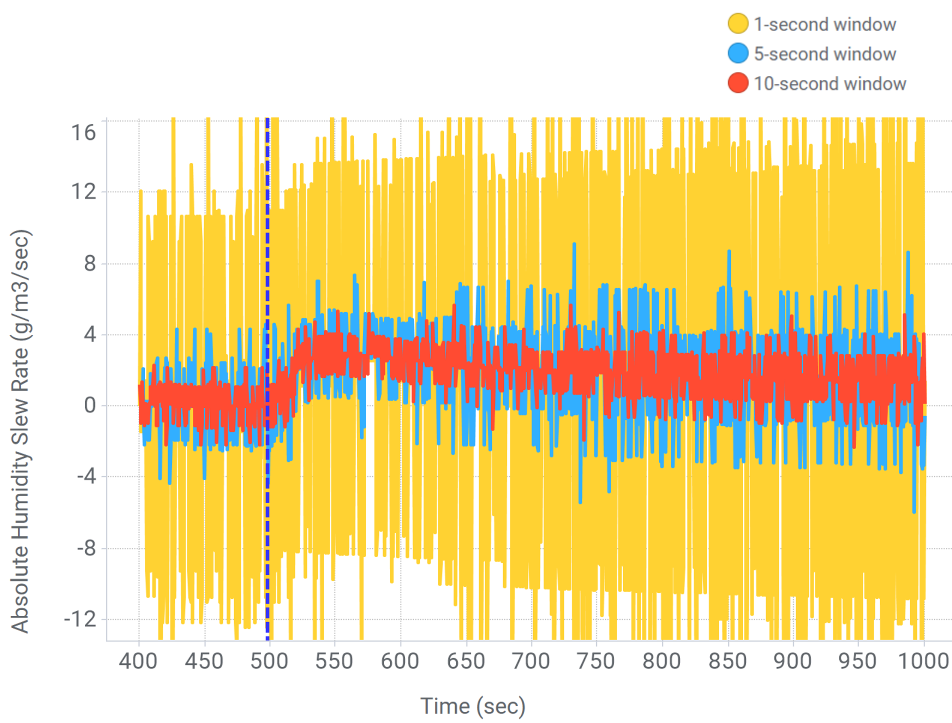

Figure 5-4. Test 2 (22°C, 45%RH, 0.07mL water): AH Slew Rate Calculated Across Different Time Windows

Furthermore, the test results confirmed that a greater volume of water induces a larger change in RH, resulting in a larger peak RH slew rate. Figure 5-5 and Figure 5-6 compare the response for all 3 water volume tests at indoor ambient conditions, where the ingress events have been normalized to occur at time = 0. The full flow (100mL) and 3 drop (0.07mL) events are easily distinguishable using the RH 10-second slew rate. The one drop (0.023mL) event also had a noticeable increase in RH slew rate, however the data was noisier. Thus, this is difficult to reliably distinguish a single-drop ingress event from normal ambient humidity fluctuations using an RH slew rate threshold, as shown in Figure 5-6. This shows that the slew rate threshold can be used to detect small volumes of water ingress ≤0.07mL, however there can be limitations in detecting even smaller water volumes.

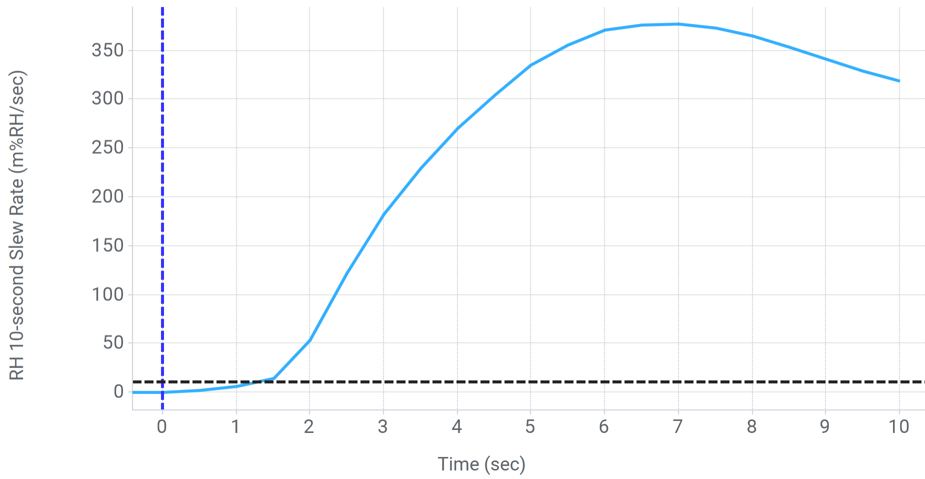

Figure 5-5. Test 3 (22°C, 50%RH), Full Flow (100mL) Test

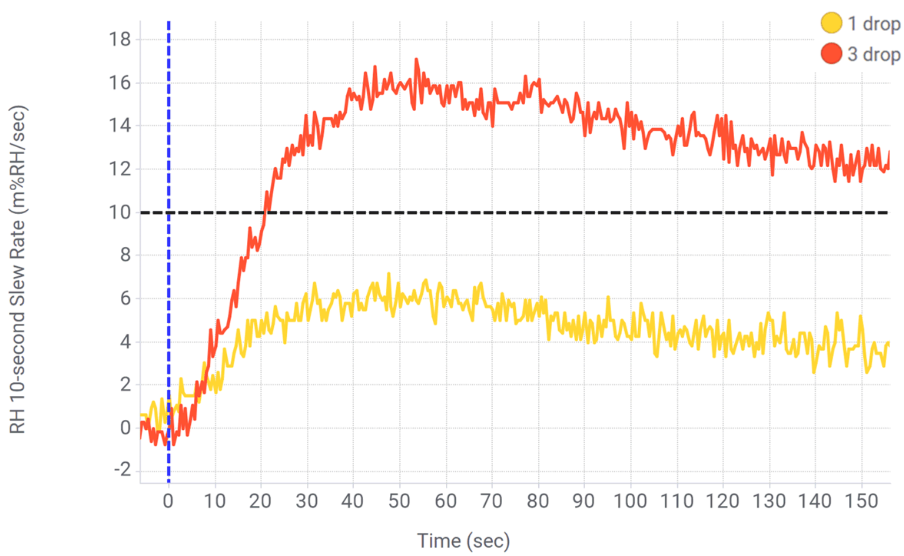

Figure 5-6. Tests 1-2 (22°C, 45%RH), 1 Drop (0.023mL) and 3 Drop (0.07mL) Tests

The full flow ingress event was also repeated at indoor ambient temperatures and elevated humidity levels of 70%RH. Figure 5-7 shows the response for the full flow ingress event at 70%RH, where the ingress event have been normalized to occur at time = 0. At higher RH, the change in RH slew rate due to the ingress event is less pronounced but still comfortably exceeded the 10m%RH/s threshold, and is thus distinguishable from typical ambient fluctuations.

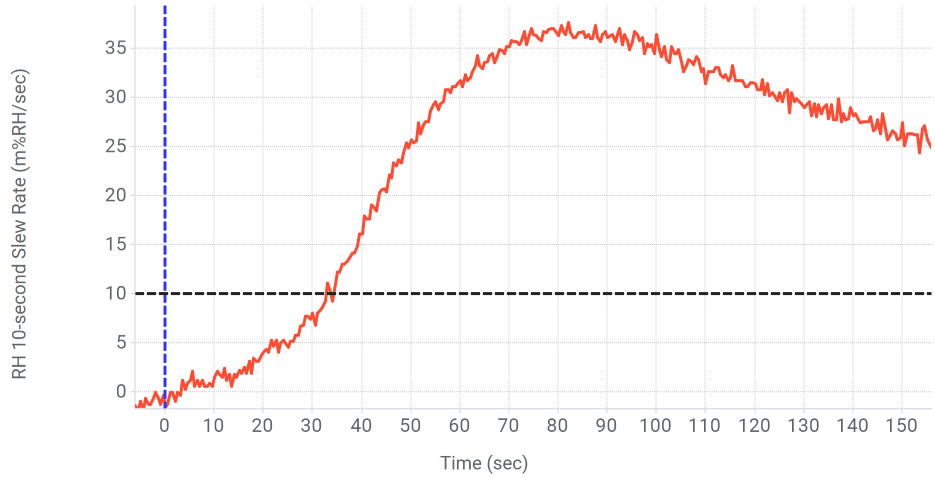

Figure 5-7. Test 4 (22°C, 70%RH), Full Flow (100mL) Test

5.2 Test Results at Hot and Cold Temperature Conditions

Next, the HDC3020 was tested overtemperature to make sure that the HDC3020 can reliably detect a small volume of water ingress. After studying the three-drop test data at varying conditions, the slew rate threshold of 10m%RH/s was chosen to detect a water ingress event for the given test enclosure.

The results for the three drop tests across all temperature and humidity conditions are summarized in Table 5-1 and Figure 5-8. In all cases, the ingress event was detected within 40 seconds, and in most cases within a few seconds. As shown, drier conditions produced a much higher peak RH slew rate (up to 106.0m%RH/s in cold, dry air) compared to more humid starting conditions. Drier conditions also allowed the ingress event to be detected more quickly, as fast as 1.5sec in hot, dry air (using a 2Hz automatic measurement rate). The peak slew rates at cold temperatures were higher than at hot temperatures; for example, compare the cold or humid and hot or humid test results. This behavior can be explained because the equilibrium saturation vapor pressure is lower at cold, so the environment's capacity for water moisture is lower, thus small changes in water content result in larger changes in RH. Even in the worst-case tested scenario at hot and humid conditions, the humidity spike caused by the ingress event (22.6m%RH/s) comfortably exceeded the 10m%RH/s threshold. This confirms that the chosen threshold is appropriate across a range of realistic environmental conditions.

Table 5-1. Test Summary for Three-Drop (0.07mL) Tests across All Tested Conditions

Test Condition	Peak RH 10-second Slew Rate	ΔTime to Ingress Detection
22°C, 45%RH (Indoor ambient)	17.1m%RH/s	21.0s
50°C, 20%RH (Hot and dry)	78.1m%RH/s	1.5s
50°C, 70%RH (Hot and humid)	22.6m%RH/s	38.5s
10°C, 10%RH (Cold and dry)	106.0m%RH/s	3.5s
10°C, 70%RH (Cold and humid)	96.4m%RH/s	3.5s

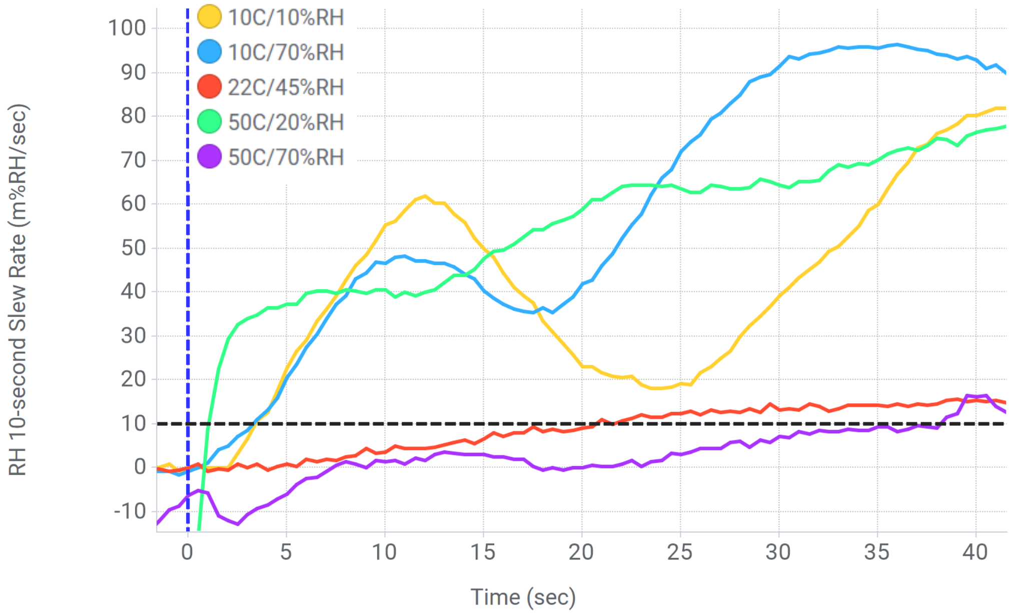

Figure 5-8. Three-Drop (0.07mL) Test Across All Tested Conditions

5.3 Vent Submersion and Air Exchange Tests

Additional testing was performed on the vented test enclosure to make sure that changes in RH can reliably be attributed to true ingress events, and false alarms does not occur due to normal fluctuations in the ambient humidity. First, the vent was submerged in water to verify the integrity of the waterproof vent. The vent prevented any water from entering the test enclosure and slowed down the moisture exchange. As a result, the RH remained essentially flat (see Figure 5-9).

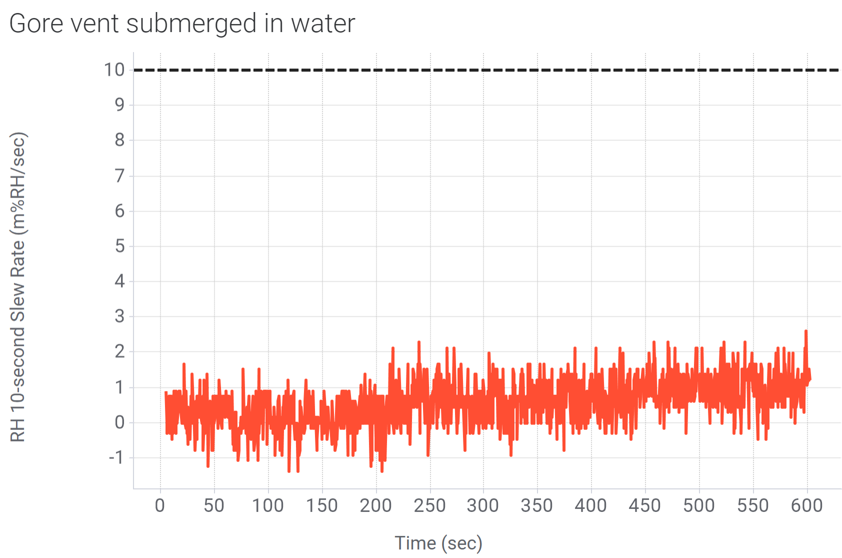

Figure 5-9. Vent Submersion Test: RH 10-second Slew Rate vs. Time

For the second test, the vented enclosure was acclimated to indoor ambient conditions of about 23.5°C and 44%RH. Then, the enclosure was closed and placed inside of the environmental test chamber, which was preset to high humidity conditions of 90%RH at 25°C. The HDC3020 was observed to see how fast the RH reading can increase. As shown in Figure 5-10, the RH 10-second slew rate did not increase over time as quickly as a true water ingress event, and remained much lower than the threshold. This demonstrates that with a properly vented enclosure, this is possible to distinguish leaks from normal humidity increases without triggering a false alarm.

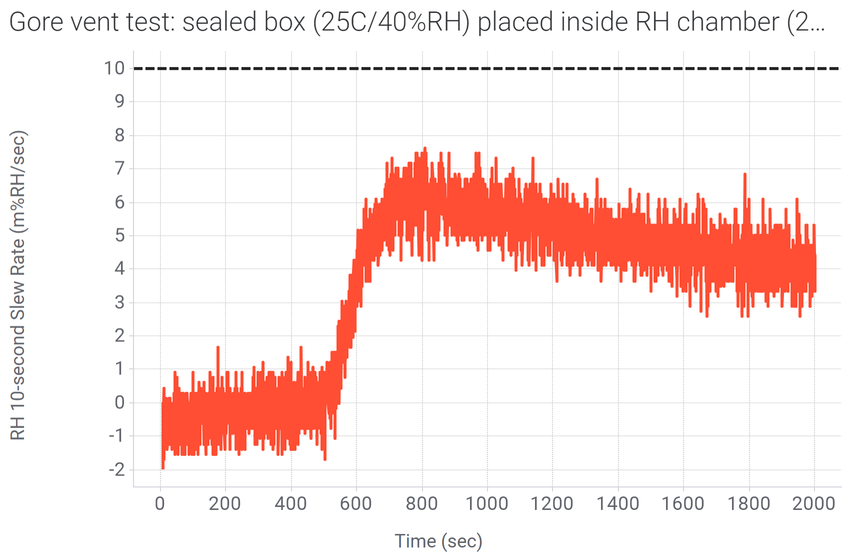

Figure 5-10. Air Exchange Test Between Vented Enclosure and Environmental Chamber: RH 10-second Slew Rate vs. Time

6 Summary

Using a humidity sensor, such as HDC3020, presents a new method for water ingress and leak detection based on an RH slew rate detection algorithm. A sharp rise in relative humidity (measured as an RH 10-second slew rate) signals a water leak. This method allows a single sensor to cover the whole enclosure by sensing water vapor, catching leaks regardless of where the leaks occur. These findings can be applied to both semi-open and closed systems.

Extensive testing across temperatures 10–50°C and humidity 10–70%RH demonstrated that even a small leak (0.07mL of water in a 1.7L enclosure) triggers a clear humidity spike. A threshold of 10m%RH/s reliably detected such leaks in less than 40 seconds using the tested 1.7L enclosure, while avoiding false alarms from ambient humidity changes. The method was also robust across all tested conditions, including hot/cold and humid/dry extremes. This approach provides early warning of leaks and water ingress with minimal hardware, employing only a small humidity sensor and simple firmware logic. This outperforms traditional methods by detecting water ingress anywhere in the enclosure and by differentiating true leaks from background humidity drift.

The HDC3x product family (including automotive-grade variants such as HDC3020-Q1) is TI's latest generation of humidity sensors and is suggested to implement this leak detection method. The HDC3020 digital RH sensor and HDC3120 analog-output RH sensor are both available in a standard open cavity WSON package. Also available are package variants HDC3021 and HDC3022, which offer the same electrical and RH performance as HDC3020. Notably, the HDC3022 includes an IP67 rated PTFE filter to protect the center cavity from dust and water. This water detection algorithm is not only easy to implement, but this can be adjusted for different enclosure volumes and anticipated amounts of water entering a system. Making sure the enclosure is either sealed or properly vented prevents large ambient humidity swings, so that any leak-induced humidity rise is much more pronounced than normal environmental changes. The test results indicated that the detection algorithm can use a slew rate threshold of 10m%RH/s, however the designed for threshold needs to be adjusted based on empirical evaluations of a specific enclosure size's air volume and the required sensitivity (for example, amount of water ingress that must be detected).

Figure 6-1. HDC3x Product Family Package Options

7 References

1. Texas Instruments, *HDC3x Silicon Users Guide*.
2. National Climatic Data Center, *Improved Magnus' Form Approximation of Saturation Vapor Pressure*.

8 Revision History

Changes from Revision * (June 2025) to Revision A (August 2025)	Page
• Updated the numbering format for tables, figures, and cross-references throughout the document	1
• Updated *equation 4*	7