Qualification for Impedance-based Rain Detectors
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Abstract

Detection of rain is one of the essential weather factors that are monitored by automatic weather stations in Korea. In this work, we studied the operation standards required for impedance-based rain detectors in terms of surface temperature and sensitivity, in an effort to establish a qualification procedure for rain detectors. The surface temperature of rain detectors was measured at varying air temperatures from −30 °C to 20 °C, considering the hypothetical presence and absence of rain/snow. In addition, the sensitivity of rain detectors was studied generating artificial raindrops of regular size. The sensitivity was evaluated in terms of the critical number of droplets that triggers the activation of the rain detector. We found that the sensitivity is affected by stationary, horizontal, and vertical droplet deposition methods. The critical number of droplets for the stationary deposition is higher than that for both horizontal and vertical depositions, which provides the maximum limit of droplets required to activate the detector. Based on our experiments considering surface temperature measurements and sensitivity tests, we suggest a revised version of surface temperature and sensitivity requirements for the qualification of impedance-based rain detectors.

Keywords: Rain detector, Surface temperature, Sensitivity, Impedance, Droplet

1. INTRODUCTION

Climate significantly affects human life and activity, as well as biological and geological systems on earth. Previously, there have been tremendous efforts to measure and forecast weather factors such as temperature, pressure, and rainfall [1]. For surface weather observation, automatic weather stations (AWS) are used to monitor several essential weather factors including temperature, wind direction, wind speed, pressure, rain detection, and precipitation amount. In the case of rain detection, the Korea Meteorological Administration (KMA) specifies standards indicating that rain detectors should have gold electrodes and be either of impedance or capacitance type, have an inclination angle between 15 ° and 30 °, operate at temperatures ranging −50 °C to 50 °C, among others [2]. Although the standard requirements are more specific than those mentioned, a detailed procedure to qualify the operation of rain detectors has not been prepared yet. For instance, the surface temperature of rain detectors with varying air temperature, the generation of artificial droplets, and the size of droplets might affect the operation and sensitivity of rain detectors [3]. Thus, the objective of this study was to establish a qualification standard for rain detectors.

Here, we focus on two aspects of rain detectors: surface temperature measurements at varying air temperature and sensitivity tests by the generation of artificial droplets. The first aspect, related to the surface temperature measurement, is important because keeping a certain level of surface temperature prevents the formation of dew or frost on the surface of rain detectors. This way, the dew and frost can be distinguished from actual rain and snow, respectively. The measurement is performed by varying the surrounding air temperature from −30 °C to 20 °C inside a chamber considering hypothetical presence and absence of rain/snow. For the second aspect, related to the sensitivity tests of rain detectors, it is important to generate artificial raindrops having a uniform size for consistency, because the actual size of raindrops varies significantly [4]. In addition, since droplet deposition methods may affect the sensitivity of an impedance-based rain detector, three different droplet deposition methods (stationary, horizontal, and vertical) with respect to the electrode direction on the detector were tested. Then, the sensitivity of the rain detector was evaluated in terms of the...
critical number \((N)\) of droplets that activates the rain detector. Based on the experimental results, a qualification procedure for rain detectors is discussed.

2. EXPERIMENTS

2.1 Temperature measurements of the rain detector surface and surrounding air

To control the temperature of surrounding air down to \(-30^\circ C\), a commercial freezer (Stirling Ultracold) was used as the test chamber, where the rain detector operated for surface temperature measurements (Fig. 1(a)). The freezer can decrease the temperature of its chamber down to \(-86^\circ C\) within a few hours. The temperature of the rain detector surface and surrounding air inside the chamber was measured at different points using T-type thermocouples. The air temperature was measured at the four corners of the chamber, whereas the detector surface temperature was measured at its four corners and surface center (right-hand picture in Fig. 1(a)). The temperature of the test chamber was first reduced to about \(-40^\circ C\). Then, the heater of the rain detector was activated, and the temperature of the chamber increased to about \(-30^\circ C\). Finally, the freezer was deactivated to slowly raise the temperature of the chamber up to room temperature (about \(20^\circ C\)). All these processes took about 6 hours, and the temperature of the rain detector surface and the surrounding air was simultaneously recorded using a LabVIEW program.

2.2 Experimental setup for the sensitivity tests

The sensitivity tests consisted of five different components as shown in Fig. 1(b): 1) a droplet dispenser for the generation of artificial raindrops, 2) a dispenser controller, 3) an impedance-based rain detector, 4) an oscilloscope to detect the rain detector activation, and 5) a microbalance to calibrate the droplets mass. We used a plunger pump droplet dispenser (Musashi Engineering Inc., Japan) that is capable of controlling both the volume of discharging liquids (water in this study) and time (2 seconds per...
droplet). In addition, the droplet dispenser has a XY stage to hold or move the rain detector laterally.

2.3 Operation of the impedance-based rain detector

The rain detector (Jinyang Industrial Co., Korea) used in this study is shown in Fig. 1. Its operation principle is based on sensing the impedance change between interdigitated Au electrodes when droplets are deposited to connect some of the separated electrodes. The electrode width ($w_e$) and gap ($w_g$) between two electrodes are $w_e = 1$ mm and $w_g = 0.5$ mm, respectively, as shown in the inset of Fig. 1(c). When the impedance meets a certain critical value, the rain detector changes its output from Off (0 V) to On (5 V) state. This output change was registered by an oscilloscope.

2.4 Calibration of the droplet mass

In order to determine the exact size of droplets, it is required to calibrate the droplet dispenser. In this regard, we compared the discharging volume of water commended by the dispenser controller with the weight of the generated droplets measured by a microbalance. Throughout this study, deionized (DI) water (density = 1 g/cm$^3$) was used, and thus the volume and weight of droplets were easily converted into their size, assuming that each droplet is a perfect sphere.

3. RESULTS AND DISCUSSION

3.1 Results

According to the meteorological statute book by the KMA [2], the operation standards for surface temperature of impedance-based rain detectors are as follows:

1) When there is no rain or snow, the surface temperature of rain detectors should be 15 °C for air temperature ranging from −30 °C to 0 °C, and the surface temperature should be higher than 15 °C when the air temperature is higher than 0 °C.

2) When there is rain or snow, the surface temperature of rain detectors should be maintained at (air temperature + 50) °C.

The main purpose of the above requirements for the surface temperature of rain detectors is to prevent the formation of dew and frost to distinguish them from actual rain and snow, respectively.

The surface temperature of rain detectors was first measured under the condition of no rain or snow at varying air temperature from −30 °C to 20 °C, as shown in Fig. 2(a). The temperature of the rain detector surface and surrounding air inside the chamber was measured as detailed in Section 2.1. When the air temperature decreased to about −40 °C, we activated the heater of the rain detector and then adjusted the air temperature to about −30 °C. Once the heater was activated, the surface temperature of the rain detector quickly increased above 0 °C. However, only one measurement point (i.e., the central point) of the rain detector surface was 15 °C higher than the air temperature for the whole range of air temperature (−30 to 20 °C), as shown by the difference between the surface and air temperature in Fig. 2(b).

Next, we repeated a similar temperature measurement under presence of hypothetical rain/snow (Fig. 3(a)). When the rain detector determines that there is rain or snow, the power of the heater is elevated so that they can be quickly melted or evaporated. In order to establish the hypothetical rain/snow condition, some of the electrodes of the rain detector were connected with a conducting tape to activate it. When the heater was operating at the air temperature of −40 °C, the air temperature was adjusted to about −30 °C and slowly increased to about 20 °C. In this hypothetical rain/snow condition inside the chamber and due to the elevated power consumed by the heater, the surface
temperature of the rain detector was higher than \((50 + \text{ air temperature}) \, ^\circ\text{C}\) at four measurement points as shown in Fig. 3(b).

We then studied how the sensitivity of rain detectors can be evaluated. First, it was important to generate regular artificial droplets of a desired size and frequency. We used a liquid dispenser having a typical needle to generate uniform droplets and calibrated it to ensure traceability to the SI unit in terms of the droplet mass. We compared the commended value with the actual droplet mass using a microbalance. Fig. 4(a) shows that the commended value by the dispenser controller suitably agrees with the measured value. The calibration of the droplet mass generated by the dispenser is summarized in Table 1. The error between the commended and measured values up to five droplets was approximately 1%. The diameter \((D)\) of a single droplet was calculated to be \(D = 2.06 \, \text{mm}\) under the assumption that the droplet is a perfect sphere. Fig. 4(b) shows the picture of the generated droplet used for the sensitivity tests.

Using uniformly-generated artificial droplets, the rain detector sensitivity was tested using three different deposition methods: 1) stationary deposition, where multiple droplets are deposited on a specific area and allowed to merge into a larger single droplet (left-hand picture in Fig. 5(a)); 2) horizontal deposition, where each droplet is deposited in parallel to the electrodes (middle picture in Fig. 5(a)); and 3) vertical deposition, where each droplet is deposited along the direction perpendicular to the electrodes (right-hand picture in Fig. 5(a)). It should be noted that in all the deposition methods, the first droplet was arbitrarily deposited on the rain detector surface.

Then, we registered the minimum number of droplets required to activate the rain detector, called the critical number, as shown in the inset of Fig. 5(b). As a result, we found that the critical number for stationary deposition \((N_s)\) is higher than that for both horizontal and vertical depositions \((N_h\) and \(N_v\), respectively), as shown in Fig. 5(b). In contrast, the critical numbers for horizontal and vertical depositions are similar to each other \((N_h \approx N_v)\). Note that \(N_s\), \(N_h\), and \(N_v\) were obtained by averaging data from 10 corresponding experiments. Since the critical number can represent the rain detector sensitivity in terms of the total number of droplets required for a signal switch, we focused on studying the physical mechanisms underlying the rain detector sensitivity.

For better understanding, droplets on electrodes and their physical dimensions in cases of stationary and horizontal deposition are illustrated in Fig. 6(a) and Fig. 6(b), respectively. In

### Table 1. Calibration of the mass of droplets generated by the droplet dispenser

| Number of Droplets | A. Commended value (mg) | B. Measured value (mg) | C. Error (%) = \((A-B)/A\times100\) |
|--------------------|-------------------------|-----------------------|----------------------------------|
| 2                  | 9.2                     | 9.18 ± 0.06           | 0.217                            |
| 3                  | 13.8                    | 13.66 ± 0.07          | 1.014                            |
| 4                  | 18.4                    | 18.25 ± 0.05          | 0.815                            |
| 5                  | 23                      | 22.73 ± 0.17          | 1.174                            |
the stationary deposition, the droplets from the dispenser merge into a single droplet with lateral dimension \( l \), whereas in the horizontal deposition, the lateral dimension of a single droplet is \( s \). Assuming that the shape of both \( s \)- and \( l \)-sized droplets is similar and the only difference is their volume, a relationship between \( l \) and \( s \) can be obtained as

\[
l = s \cdot \frac{N_s}{N_h},
\]

because the volume of a \( l \)-sized droplet \((v_l)\) is \( N_s \) times bigger than that of a \( s \)-sized droplet \((v_s)\) \((v_l = v_s \cdot N_s)\). Since the impedance change between electrodes is mostly due to the in-plane water (region \( A \) in Fig. 6(c)) rather than the out-of-plane water (region \( B \) in Fig. 6(c)) \([5]\), the total area of region \( A \) covered with droplets will contribute to the impedance change of the rain detector. Therefore, the total area \((A_t)\) of region \( A \) for a \( l \)-sized droplet and \( s \)-sized droplets (total \( N_h \)) should be same when the critical impedance is reached:

\[
A_t = \pi \left( \frac{l}{2} \right)^2 \times \frac{w_g}{(w_g + w_e)} = \pi \left( \frac{s}{2} \right)^2 \times \frac{w_s}{(w_g + w_e)} \times N_h.
\]

By the relationship between \( l \) and \( s \) in Eq. (1), Eq. (2) becomes

\[
N_s = N_h^{\frac{3}{2}}.
\]

Note that the total area \((A_t)\) of region \( A \) is proportional to \( w_g/(w_g + w_e) \) in Eq. (2), because for each type of deposition, the first droplet is deposited on an arbitrary point of the rain detector. Following the same reasoning, the horizontal and vertical depositions are equivalent, hence \( N_h = N_s \). This is consistent with the results observed in Fig. 5(b).

In Fig. 7, we compare the theoretical consideration from the analysis above (solid line) with the experimental results (square dots). In general, the experimental data follows the theoretical curve, confirming the validity of our theoretical approach. Note that each dot was obtained from the average of 10 experiments.

3.2. Discussion

The required surface temperature of the rain detector is higher in the presence than in the absence of rain/snow, as specified in the meteorological statute book. In principle, the surface temperature of rain detectors should be higher than the air temperature to prevent the formation of dew or frost. However, since the rain detector heater consumes most of the power in the AWS, a proper level of surface temperature is desired. In addition, since we measured the surface temperature on 5 points and found some temperature difference among them, it is important to consider the detector area that should meet the surface temperature requirement. Based on our experiments, we suggest operation standards for rain detectors regarding the surface temperature as follows:

1) When there is no rain or snow, the surface temperature of rain detectors should be maintained above 15 °C on the surface for air temperatures ranging from −30 °C to 0 °C, and the surface temperature should be higher than (air temperature + 15) °C for air temperatures higher than 0 °C.
2) When there is rain or snow, the surface temperature of rain detectors should be maintained above (air temperature + 50) °C for air temperatures ranging from −30 °C to 0 °C, and above 50 °C for air temperatures higher than 0 °C.
Our reason to change requirement 1) is given by the difficulty to maintain the surface temperature exactly at 15 °C for air temperatures ranging from −30 °C to 0 °C. Therefore, it is convenient to consider temperatures of 15 °C and above. However, maintaining the surface temperature above 15 °C cannot always prevent the formation of dew, for example, at an air temperature of 30 °C. In this regard, the surface temperature should be higher than (air temperature + 15) °C for air temperatures higher than 0 °C. Nevertheless, this additional statement is not a harsh requirement, considering our measurements. For instance, the surface temperature is higher than (air temperature + 15) °C at one point for an air temperature higher than 0 °C when there is no rain or snow (Fig. 2(b)).

When there is rain or snow, requirement 2) of the revised version on surface temperature lessens for air temperatures higher than 0 °C. That is, for air temperatures higher than 0 °C, maintaining the surface temperature above 50 °C, instead of (air temperature + 50) °C, is enough to quickly evaporate the raindrops on the surface. This aims at reducing the power consumption of the rain detector heater.

In the sensitivity test, the generation of uniform artificial droplets is a key aspect, since droplets with irregular size can affect the sensitivity in terms of the critical number of droplets that trigger a change in the detector state. The results using uniform droplets show that the sensitivity can be affected by the method of droplet deposition. Since the critical number of droplets for the stationary deposition ($N_s$) is higher than those for the other two methods, $N_s$ may provide the maximum limit of droplets required to activate the detector. Moreover, because the resistivity of rainwater is much smaller than that of the DI water used in this study, $N_s$ suitably represents the maximum number of droplets required to activate the detector. Therefore, we can conclude that the rain detector should be activated with 13 droplets, regardless of the type of water or the deposition method, according to the result shown in Fig. 5(b).

4. CONCLUSIONS

We have studied operation standards for impedance-based rain detectors in relation to the surface temperature and sensitivity in an effort to establish a qualification procedure for rain detectors. The rain detector surface temperature was measured considering presence and absence of rain/snow at varying air temperatures ranging from −30 °C to 20 °C. The current requirements for surface temperature were revised based on our actual measurements in order to prevent dew or frost formation, as well as reduce the heater power consumption. In addition, the sensitivity of the rain detector was studied in terms of the number of droplets required to activate the rain detector. We found that the droplet deposition methods affect the sensitivity of an impedance-based rain detector. Among the three different methods of stationary, horizontal, and vertical droplet deposition, the critical number obtained for stationary deposition ($N_s$) was higher than that for horizontal and vertical depositions ($N_h$ and $N_v$, respectively). This provides the maximum limit of droplets required to activate the detector. Finally, we have provided a theoretical explanation for the difference between $N_s$ and $N_h$ that suitably agrees with the experimental data. A more sophisticated study on the exact surface temperature for a rain detector to avoid the formation of dew and frost will be necessary in order to minimize the heater power consumption. In addition, using randomly scattered droplets will be useful to mimic actual raining situations. Our results can be beneficial as a reference to establish a generic qualification procedure on other types of rain detectors such as optical-based rain detectors [6].

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