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Experimental study of relative permittivity of atmospheric ice

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Abstract

Atmospheric icing on onshore and offshore structures is problematic, if we don't detect and remove it. Despite of various ice detection techniques, capacitor based ice sensing technique is interesting one, as it is based on dielectric properties of material. This technique of measuring icing event is simple and cost-effective. Based on the dielectric concept, an experimental setup comprised of two rectangular aluminum bars in parallel connected with an LCR meter, thermocouples, data acquisition system and computer was designed at the cold room chamber facility of Narvik University College to study the transient response of dielectric constant of ice at different operating atmospheric conditions. Analysis showed that depending on the atmospheric ice type the capacitance varies due to the variation in temperature.

Keywords: Atmospheric ice; Capacitance; Dielectric constant; Temperature; Velocity.

1. Introduction

In cold regions, the study of ice accretion on structures is an important issue as this can cause severe damage. Such structural damage or its function failures can be expensive and dangerous for both human and the industrial terms [1]. For example ice accretion on power lines can lead to the loss of industrial resource due to faults on overhead transmission lines grid system. Similarly icing can cause problems to transmission towers used for communication and broadcasting, as it results in distortions of transmitting data and weakening signals or even tower collapse. Aircrafts or helicopters also can face the dangerous situation due to the ice accumulation [2]. This needs suitable ice mitigation, which should have detection technique before to it. The ice detection process is having the same importance as the ice removing techniques. A robust technique to detect and measure ice accretion on structures is a challenging task. Till now, there is no ice sensor commercially available in the market that can detect and measure all important icing parameters such as icing rate, load and type under severe icing conditions simultaneously. The main purpose of an ice detector is to detect and indicate the rate of an icing event. Depending on the type of accreted ice, glaze or rime, de-icing power requirements will be different, therefore it is important for ice detection sensor to distinguish between rime and glaze ice. Different ice measurement system has different use, some of the ice instruments measure icing rate, some measures the weight of ice and some indicates if an icing event is ongoing.

The ice detection methods can be categorized as direct methods and indirect methods. The indirect methods of ice detection involve measuring weather conditions such as humidity, temperature, pressure, etc. that create a surrounding for an icing event to occur. For example, reduction in the power generated by the wind turbine, reduction in the speed of anemometers or measuring the variables that cause icing or variables that correlate with the occurrence of icing, such as cloud height and visibility . Empirical or deterministic models are then used to determine when icing is occurring. The direct methods of ice detection are based on the principle of detecting property changes caused by ice accretion. Examples of such properties include mass and dielectric constant. Since early 80's many researchers have been working on different ice detection techniques. In 1984, Chamuel J.R. has designed a system to detect the icing using ultrasonic wave detector, where he has measured the changes in flexural waves phase, amplitude and dispersion to detect the icing event [3]. Homola et al [4] studied and reviewed all ice detecting techniques used for wind turbines. This research paper is mainly focused on the capacitance based ice detection technique. Capacitive ice sensors generate an electric field to detect the presence of dielectric materials. Such electric field radiates outward around the probe and a dielectric material in close proximity of the field affects the measured capacitance. This attribute enables non-invasive measurements and minimum loading errors. Kwadwo designed a capacitance based icing sensor, which can detect the ice based on capacitance and resistance variations [5]. Kwadwo used two cylindrical probes as the capacitive sensors to detect the ice generated on the probes and measured the capacitance changes.

2. Mathematical background

The capacitance between two parallel electrodes (aluminum bars) with surface area A, separated by distance d is given as,

$$C = k\frac{A\varepsilon_0}{d} \tag{1}$$

where *k* is the dielectric constant. These two aluminum bars are separated with no material such that the dielectric constant of the air is 1. So the modified equation for the capacitance without any dielectric material placed in between is given as,

$$C_a = \frac{A\varepsilon_0}{d} \tag{2}$$

where, C_a is the capacitance of sensor with no dielectric material is present in between. If we keep the dielectric material in between the two bars, then the capacitance becomes;

$$C_d = k_1\frac{A\varepsilon_0}{d} \tag{3}$$

By substituting equation-2 in equation-3, we get

$$C_d = k_1 C_a \Rightarrow k_1 = \frac{C_d}{C_a} \tag{4}$$

From equation-4, we can say that, if any dielectric is present between the rectangular aluminum bars, the capacitance will increase with the multiplication of respected dielectric constant k. This is the basic idea for our experimentation to detect the ice accumulated on the sensor. If we can measure the capacitances before and after the dielectric present between the bars, then we can calculate the dielectric constant of that material. This will help us to find the type of ice generated on the sensor. Different types of ice will have different types of dielectric constants.
According to Kuroiwa [6], the complex dielectric constant for an applied AC voltage, given for any type of medium is,

$$k^* = k' - jk'' = C_d / C_a - jG / \omega C_a \tag{5}$$

where, C_d is the capacitance of the plates filled with dielectric medium and C_a is the capacitance with air between the electrodes, G is the conductance and ω is the angular frequency, $k` = C_d/C_a$ and $k`` = `G/_w C_a$ are the real and imaginary parts of the complex dielectric constant. The real part of the dielectric constant represents the ordinary dielectric constant (storage) and it can be defined as the volume of energy, which can be stored in a material from an external electric field. The imaginary part of dielectric constant represents the dielectric loss factor and it shows the dissipative and the loss of the material to an external electric field [7].

3. Experimental setup

Based on the dielectric concept, an experimental setup comprised of two rectangular aluminum bars in parallel connected with an LCR meter, a CCTV camera, low speed frequency controlled ice generator, high pressure air regulated water spray gun, thermocouples, weather station, data acquisition system and computer was designed at the cold room chamber facility of Narvik University College to study the transient response of dielectric constant of ice at different operating atmospheric conditions. Icing clouds (super cooled water droplets) were generated using the ice generator in cold room chamber, where the temperature can be well maintained in the range of (-30 ºC to +10 ºC).

Low speed frequency controlled ice generator used for this study can generate the wind velocities up to 5m/s, where wind velocity is operated by a variable frequency drive which has the maximum rotor frequency of 59Hz. By varying the rotor frequency, we can get different wind velocities. A simple high pressure air regulated water spray gun has been used to introduce the water droplets/mist by placing it in the spray gun hole of the tunnel. The spray gun is attached to an external air pressure pipe which can give 84 PSI pressure. This pressure is controlled by the front screw of the spray gun. It has one more screw on the back side which regulates the water content released per spray. By keeping the high pressure with low water content, we can produce the small water droplets outside the spray gun nozzle. And by keeping the low pressure with more liquid water content, we can produce the larger water droplets from the spray gun nozzle. Capacitive ice detector of two rectangular aluminum bars used for this study was placed in front of exit section of ice generator at a distance of 1 m, so that the flow gets stabilized before reaching to wind turbine model. Water droplets were introduced in the ice generator with the help of high pressure air regulated water spray gun. These water droplets get super cooled, while passing through the circular tunnel (pipe) of the ice generator and then at exit from the ice generator these super cooled water droplets collide with the surface of aluminum bars. The two rectangular aluminum bars are used as our capacitive sensors which shown in Figure 1 (d). Mounting and facing of rectangular bars is shown in Figure 1 (f) & (g). The rectangular aluminum bars are used to measure the capacitance values through the U1731C LCR Meter as shown in Figure 2. The capacitance will be measured by U1731C LCR meter which has the three selectable test frequencies 1 kHz, 120 Hz, 100 Hz. Under the selected frequency the capacitances were measured and transferred directly to the computer by using an IR-USB cable.

4. Results

Capacitance measurements and the dielectric properties of ice are dependent on temperatures. To measure the cold room temperature at different locations, we used three thermocouples to measure the temperatures at the top, bottom and middle of the cold room chamber. This helped in analyzing the results more precisely. Three thermocouples are connected to a national instrument (NI) compact data acquisition system, which in turn connected to a computer by using Lab View interface. The measured values of temperatures are listed for all experiments by using the Lab View-DAQ system. Two different types of ice (glaze and rime) were generated in the cold room chamber to study the dielectric properties of ice. Generally glaze ice is formed in the temperature range of -4 ºC- 0 ºC. To generate glaze ice in cold room chamber, we put the cold room temperature to -3 ºC and rotor fan frequency to 59Hz to maintain 4m/s wind velocity. For the spray gun we take the low pressure with high liquid water content condition, to get larger droplets out of the nozzle. Rime ice generation is possible at the temperatures of -10 ºC or less. To generate rime ice in the cold room chamber we put the cold room chamber temperature at -10 ºC and spray condition at high pressure with low liquid water content, which can provide the small size water droplets from the spray nozzle. We kept the wind velocity in a medium range of 2.5m/s to improve the droplet freezing fraction when they collide with the rectangular bar surface.

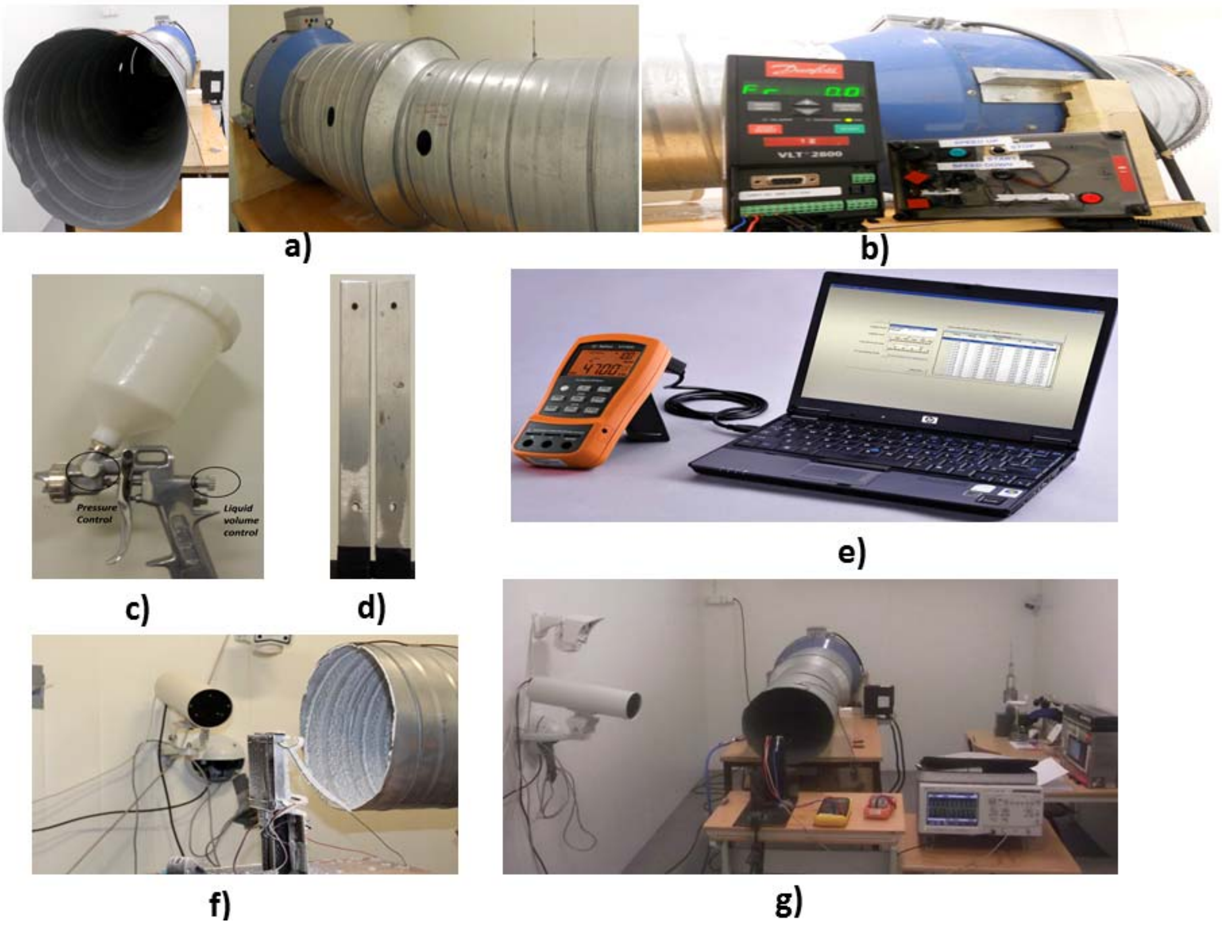

Figure 1. Experimental setup
(a) Wind tunnel spray gun holes; (b) variable frequency drive; (c) spray gun; (d) Rectangular aluminum bars; (e) LCR Meter connected to computer through IR-USB cable; (f) Sensor placement at the exit of tunnel; (g) Total view of cold room with equipment's

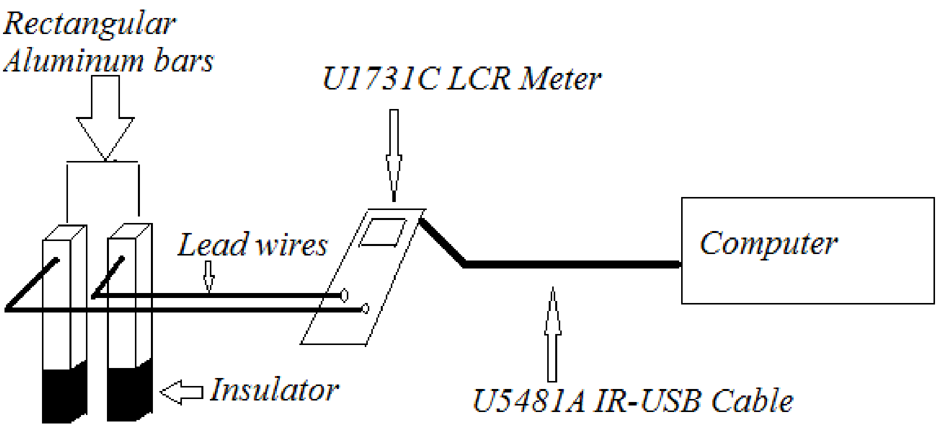

Figure 2. Capacitance values through LCR meter

4.1 Dielectric constant of glaze ice

To study the dielectric properties of wet glaze ice, we carried out analysis at temperature range of -3 ºC on two different wind velocities of 4 and 3 m/sec for large water droplets. The change in velocity was meant for the variation in the droplet freezing fraction. In case of high droplet impingement velocity the droplet freezing fraction decreases, as droplets colliding with the surface do not get enough time to get freeze. For this study the distance between both bars was set at 3 cm, whereas the frequency of the LCR meter was set at 100 Hz.

4.1.1 Case study 1

For this study the measured temperatures of cold room at top, middle and bottom ware set at -2.5 ºC, -2.59 ºC and -1.9 ºC respectively for a wind velocity of 4m/s. Large water droplets were introduced in the air to get the wet glaze ice. The generated glaze ice width was averagely at five locations of rectangular bar were 5.7cm and the thickness measured was 0.6cm. By using the measured capacitance values at test frequency of 100Hz, we calculated the dielectric constant *k*. Dielectric constant of generated glaze ice at the time of spraying liquid water is plotted as shown in Figure 3 (b). The real dielectric constant k' at the test frequency of 100 Hz was started to increase as the liquid water sprayed. The maximum value of dielectric constant achieved was 90.2, which stayed variable until it reached to 40 at the end of spraying liquid water at -3 ºC. Here the ice accumulated on the rectangular bars was detected by the increase of dielectric constant. The dielectric constant of 40 was also not stable and started to decrease after spraying was stopped. This decrease in dielectric constant was observed and plotted as shown in Figure 3 (c). After the spraying has stopped, the dielectric constant started to decrease from 40 to 4.72 and became stable after 35 minutes. This decrease in the dielectric constant was exponential and was due to the dielectric dispersion.

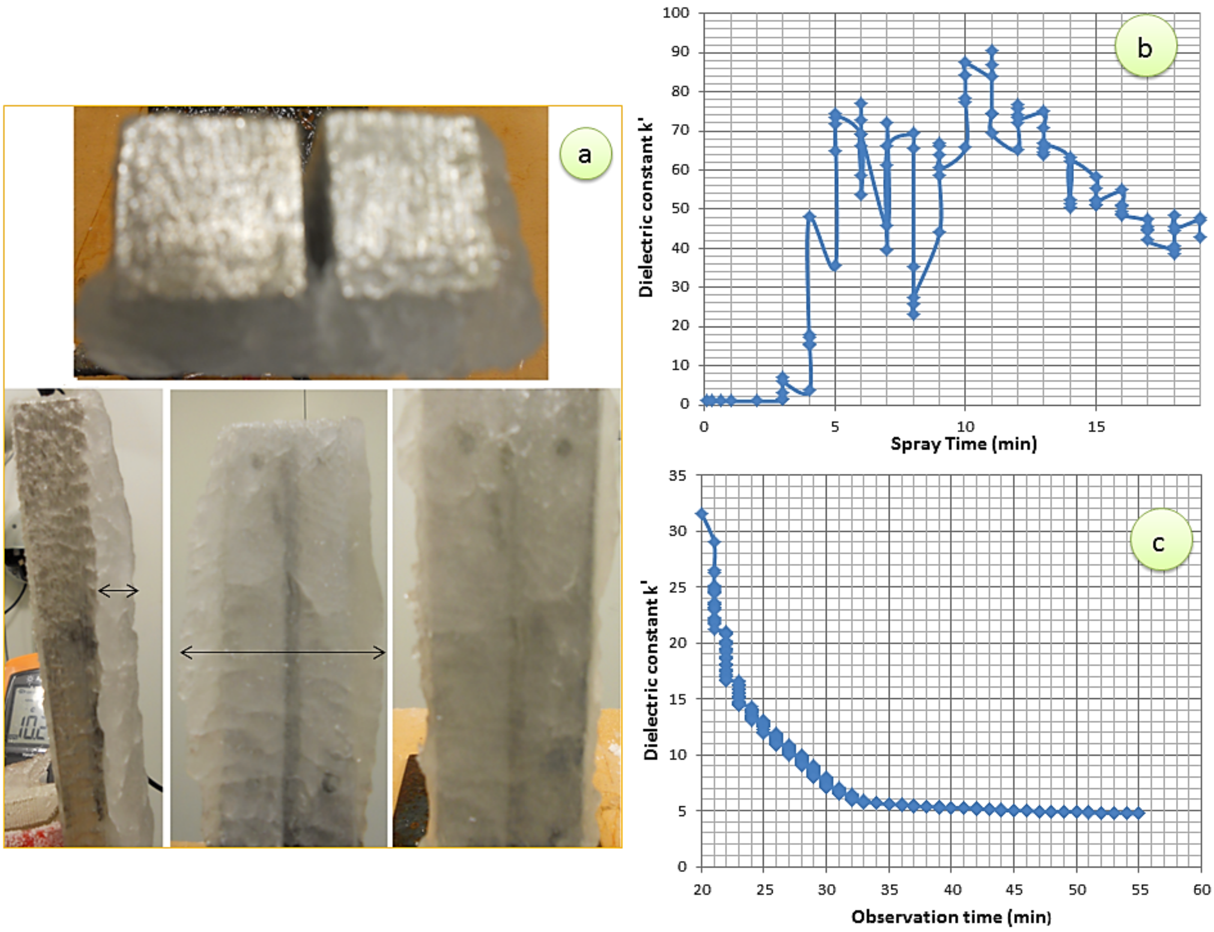

Figure 3. (a) Ice generated at -3 ºC with large water droplets at 4m/s wind velocity; (b) Dielectric constant k' at the time of spraying liquid water; (c) Observation of decreasing dielectric constant after spraying stopped

4.1.2 Case study 2

For this study the measured temperatures of cold room at top, middle and bottom ware set at -3.2 ºC, -3.11 ºC and -2.1 ºC respectively for a wind velocity of 3m/s. The glaze ice generated in this case study was not a perfect glaze ice. Lots of spikes were there with the ice, which were very hard to break with hands. The width of ice measured was 5.42 (average of 5 width values horizontally on the bars). Horizontally measured length along the sides of bars taken as thickness and the average thickness is given by 0.84cm. The real dielectric constant calculated at the time of spraying is plotted in Figure 4 (b). The peak value of the dielectric constant was 71.1 for an observed time period of 2 hours.

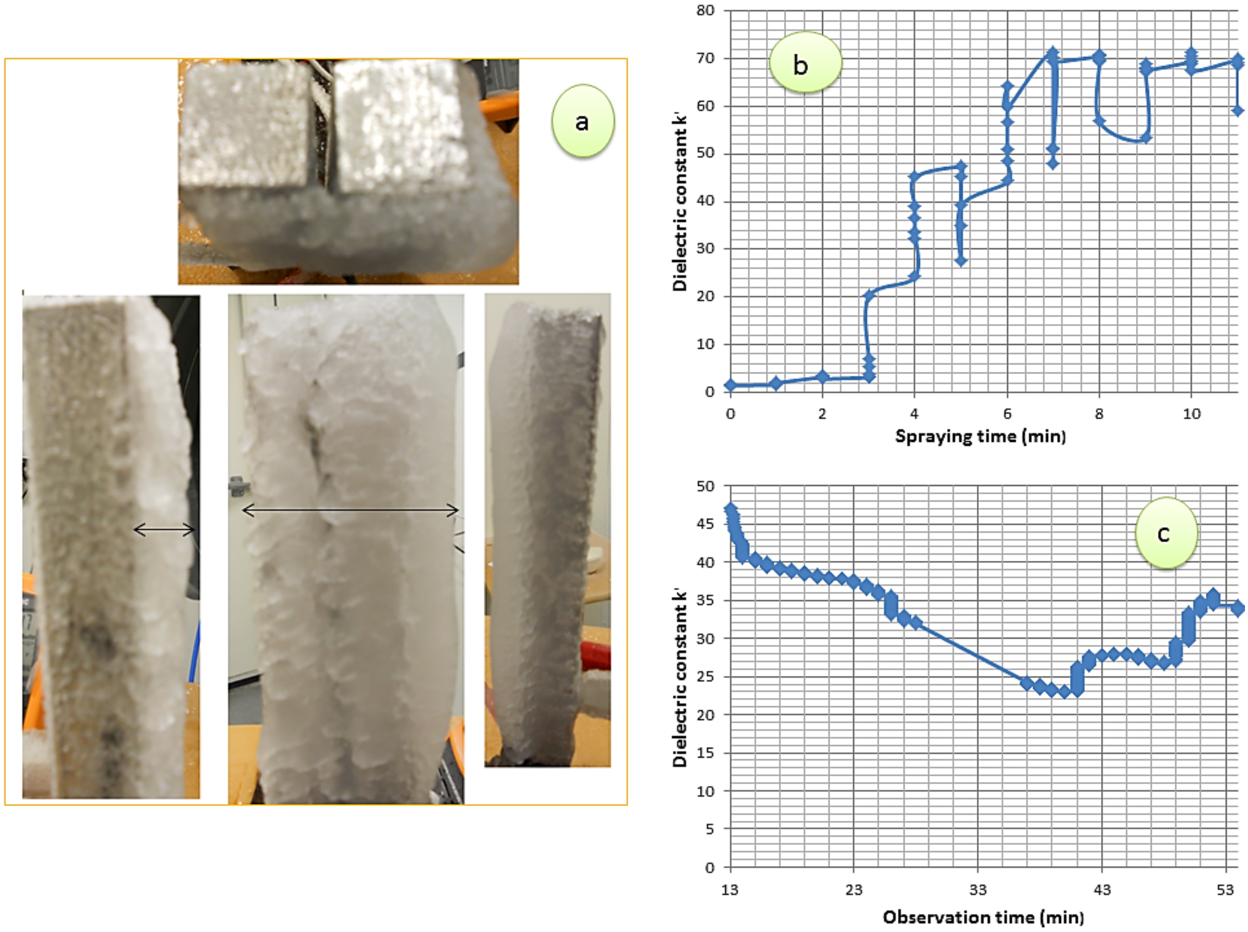

Figure 4. (a) Ice captures at -3 ºC at wind velocity of 3 m/sec; (b) Real dielectric constant *k'* at the time of spraying liquid water at -3 ºC; (c) Observation of decreasing dielectric constant after spraying stopped

4.2 Dielectric constant of rime ice

4.2.1 Case study 1

To study the dielectric properties of rime ice, we conducted this study at temperature range of -10 ºC for two different wind velocities. The top, middle and bottom temperatures measured by thermocouples are -10.6 ºC, -10.9 ºC, -9.3 ºC respectively. Here we keep the wind velocity to 4m/s. The analyses were carried out with low liquid water content with small droplets coming out of the nozzle. In this case study of rime ice generation was increased linearly with the spraying of water content. Thickness of the ice averaged from 5 values was 2.8cm. Plots of dielectric constant are drawn by measuring the capacitance at the same time. The ice accumulated picture is shown in Figure 5 (a). Ice accumulated at temperature -10.3 ºC, attained a dielectric constant of 41.2. After the droplet spraying was stopped, the observed dielectric variation goes on a linear decreasing curve. The dielectric constant seemed to be stable at 3.89 after 27 minutes of observation.

4.2.2 Case study 2

This case study was carried out at low wind speed of 3 m/sec, where the top, middle and bottom temperatures were set at -10 ºC, -10.61 ºC and -9.8 ºC. Rime ice obtained from this was the combination of both snow and ice. Experiment with high wind velocity (4 m/s) could generate ice with some parts of snow in it, but here the combination of both ice and snow together formed at low wind velocity (3 m/s). Dielectric constant plot at low wind velocity plotted in Figure 6 (b). It is interesting to see that, dielectric constant is varying mostly in the range of 20-30 at the time of spraying. The peak value of dielectric constant was 29.3. This peak value is lesser than the event 1 ice. Here also the dielectric constant is not going to be stable. From Figure 6 (c), we can see that, the dielectric constant was decreasing at a slow rate. This has been observed for 46 minutes and *k'* was at 8.

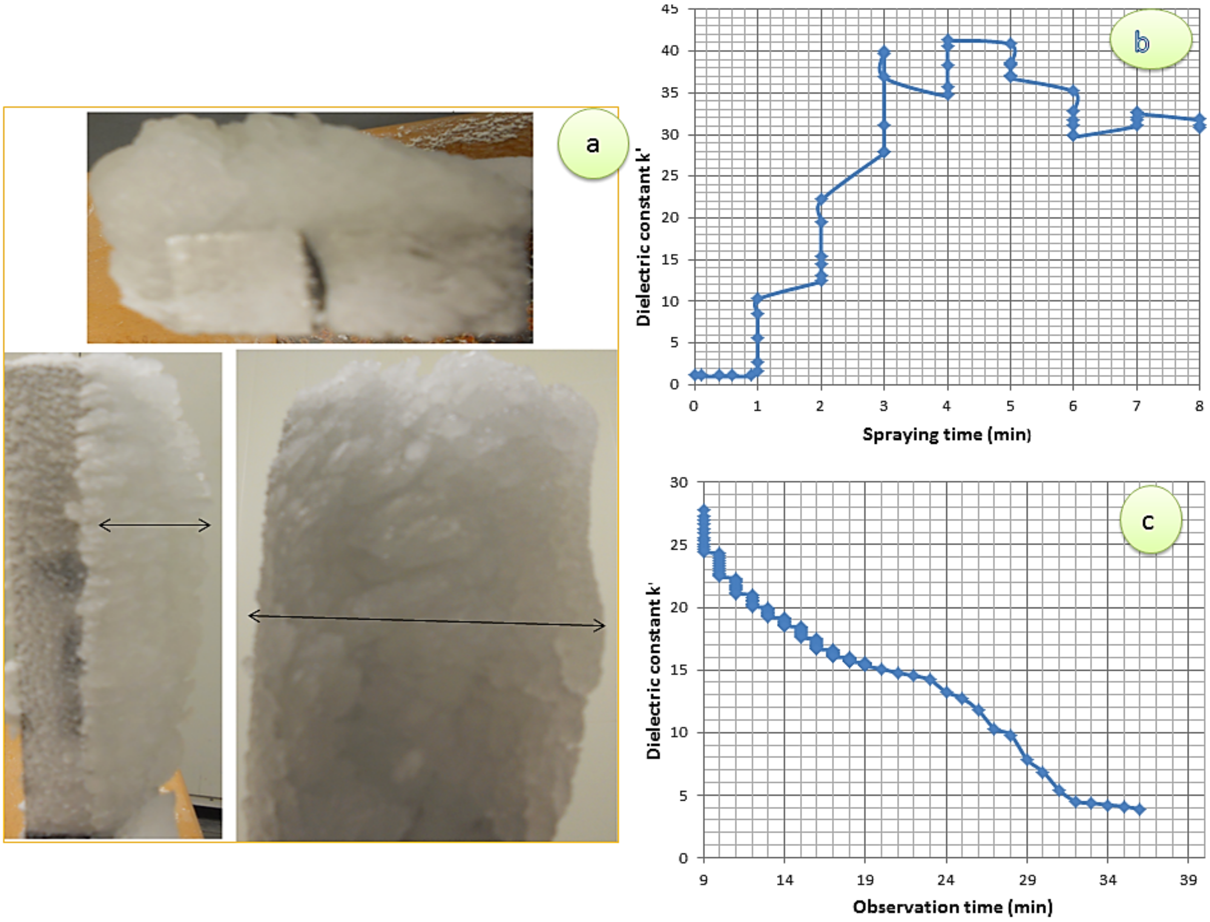

Figure 5. (a) Ice generated at -10.3 ºC with small droplets of water spraying at 4m/s wind velocity; (b) Dielectric constant plot at the time of spraying at -10.3 ºC; (c) Observation of decreasing dielectric constant after finished spraying at -10.3 ºC

4.3 Analysis

Summary of results from all the above discussed experiments is presented in Table 1. During the experimental study, we were mainly focused on real dielectric constant of the ice generated because; the LCR meter, which we used can't read the dissipation factor of 100 Hz, as its source impedance is not stable at that frequency. However, to detect and differentiate the type of ice, real dielectric constant is enough. Here from the results, we can see that the peak values of dielectric constant of ice can differentiate the two types of ice. For rime ice the real value of dielectric constant is found to be smaller as compared to the glaze ice.

From the achieved experimental results, we can say that the ice accumulated on rectangular aluminum bars is detected as the dielectric constant is increasing. The detection of ice type depends on peak value of dielectric constant. We have shown the plots of decreased dielectric constants after finished spraying. This happens because the dielectric properties of ice depends on the process by which the ice is grown [8]. It might be the impurities present at the time of icing or inclusion of gas, crumb boundaries/exterior, vacancies in the ice. The dielectric constant decreases with an observation time because of the conductivity effect in atmospheric ice as ice is behaving like an ordinary capacitor.

Table 1. Results

Ice type condition	Droplet size	Wind velocity	Peak value of dielectric constant *k'*	Thickness of ice (Average)
Glaze	Large	4 m/s	90.2	0.6cm
	Large	3 m/s	71.1	0.84cm
Rime	Small	4 m/s	41.2	2.8cm
	Small	3 m/s	29.3	3.2 cm

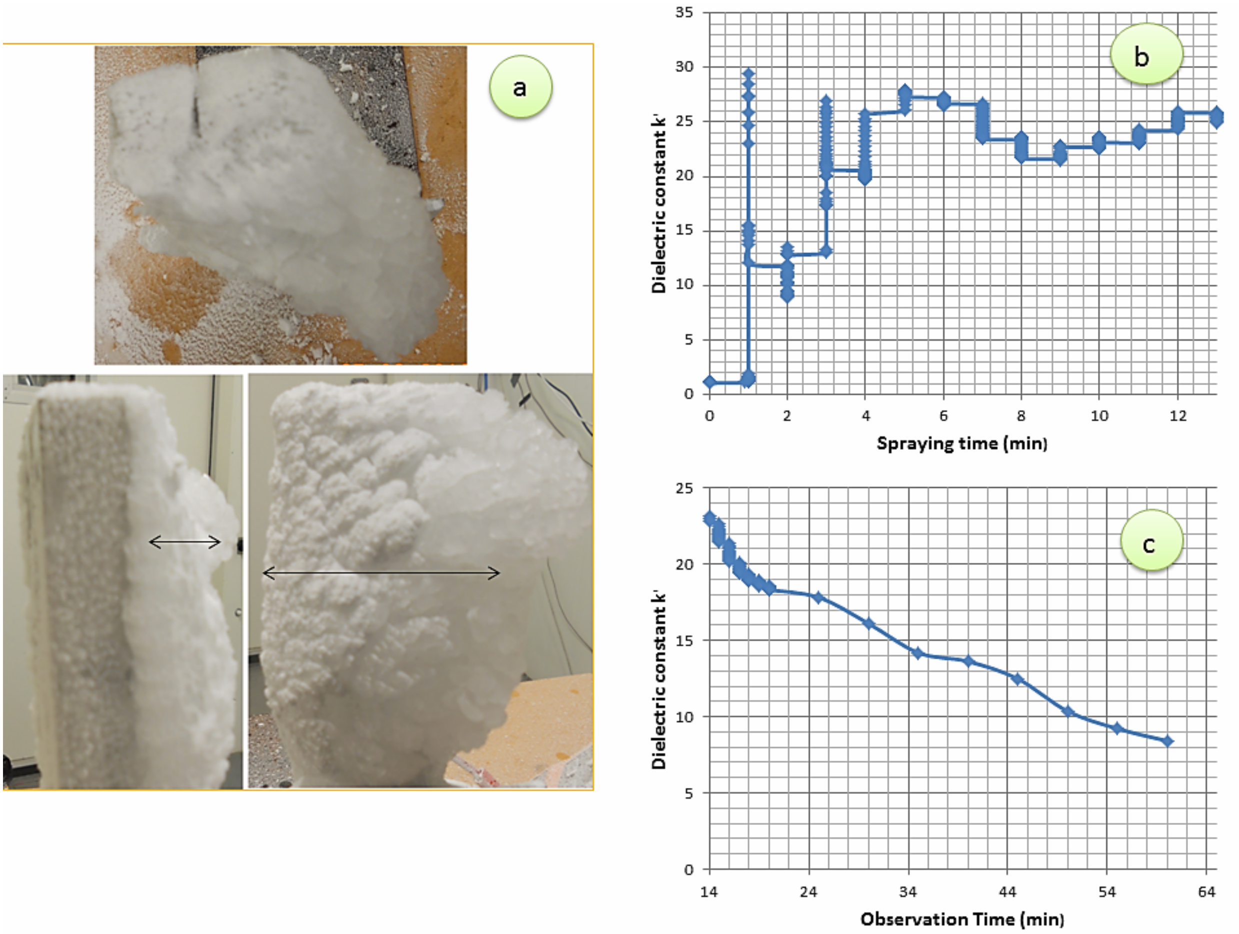

Figure 6. (a) Ice generated at -10 °C with small droplets of water spraying at 3m/s wind velocity; (b) Dielectric constant plot at the time of spraying at -10 °C; (c) Observation of change in dielectric constant

5. Conclusion

The capacitive ice sensor was tested at different temperatures and wind speeds for the rime and glaze ice conditions. Depending on the ice type it is found from the analysis of capacitance changes due to temperature variation, it was found that the capacitance decreased with a decrease in temperature. This phenomenon can help in differentiating the ice types as, glaze ice will have the higher dielectric constant and rime ice will have the lower dielectric constant than the glaze. As the dielectric constant keeps on decreasing after the icing event, therefore we couldn't get the relaxation time to trace out. But we cannot conclude that the processing of ice, we have generated had created this unstable relaxation time. No one explained this before about the long dielectric dispersion or relaxation time. It can be concluded that, ice deposition was detected promisingly by capacitive based technique and also it does have the potential to know about type of ice by considering the peak value of the dielectric constant.

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