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The Use of Capacitance to Detect Icing

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***Abstract*-The theory of capacitive ice sensing is described and requirements for a practical capacitor based icing detection system are discussed.**

I. Introduction

The Utah State Division of Water Resources currently operates several cloud seeding sites in the Utah mountains. The sites use icing probes to detect supercooled liquid water; the presence of which indicates favorable conditions for cloud seeding. Propane is released into the atmosphere when supercooled liquid water is present providing refrigeration which freezes existing water droplets leading eventually to precipitation. Accurate sensing of ice, and thus the presence of super cooled liquid water, is critical to efficient use of resource in this process.

Currently, icing probes designed for the aerospace industry are used to detect the presence of super cooled water. The probe consists of a vibrating rod which is extended into the atmosphere and ice build up on the rod causes the frequency of vibration to shift. It is this shift of frequency that is detected and processed to control propane release. When icing is detected, the decision to release propane is made, and then the current build up of ice on the probe is melted off and the detection cycle begins again. Propane is released continuously after icing is detected until an ice free cycle occurs.

The probes in use are expensive, require an AC power source, and have moderately high power requirements. The cost and power requirements of these probes prohibit widespread development of cloud seeding sites. This paper presents research on an alternative icing probe based on a capacitive measure of icing conditions. Research on this icing sensor is being sponsered by the Utah State Division of Water Resources[1].

II. Capacitive Ice Sensing

A. Fundamentals of Capacitors

Capacitors can be thought of as electric charge storage devices. A simple capacitor consists of two parallel conducting plates separated by air, see figure 1. The measure of charge storage capability is called capacitance and in the MKS system of units has unit Farads (F).

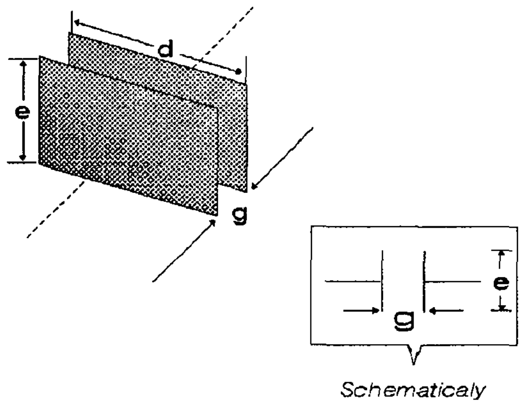


Figure 1

For a parallel plate capacitor, capacitance is given approximately by:

$$C = \varepsilon_r \varepsilon_0 A/g \quad (1)$$

where: ε_0 is the permittivity of free space
ε_r is the relative permittivity
A is the area of a plate
g is the gap between the plates

$\varepsilon_0 = 8.854\times10^{-12}$ Farads/m

for air $\varepsilon_r = 1$

The gap between the plates may also be filled with an insulating substance which is called a dielectric. In general, if the gap between the plates of a capacitor is filled with a dielectric the capacitance will be higher than an air filled capacitor of the same geometry. A dielectric has a higher relative permittivity (ε_r) than air which has a relative permittivity of 1. Sensors which make use of the dielectric properties of materials are in use, for example, a sensor which measures the degradation of engine oil by measuring the change in the dielectric constant of the oil is available commercially. Ice has a relative permittivity of 90. For example, if an air filled parallel plate capacitor has a capacitance of 1uF then the same capacitor, with the gap filled with ice, would have a capacitance of 90uF. It is a simple matter to measure capacitances which differ by two orders of magnitude..

If the gap between the plates of the capacitor is partially filled with ice the capacitor becomes essentially two capacitors connected in parallel; one which has an air filled gap and one which has an ice, or dielectric, filled gap, see figure 2.

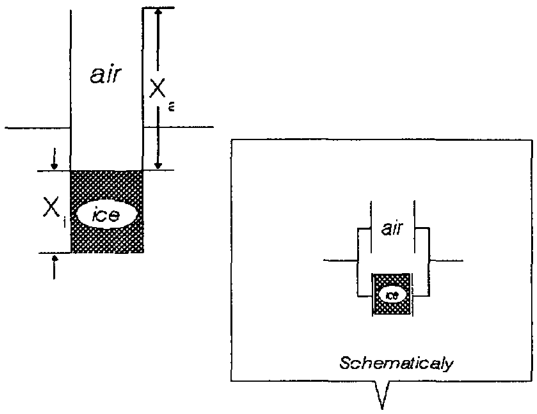


Figure 2

The capacitances of parallel capacitors add, thus the capacitance of this arrangement is given by:

$$C = \varepsilon_{ri}\varepsilon_0 x_i d/g + \varepsilon_{ra}\varepsilon_0 x_a d/g \qquad (2)$$

where x_i is the width of the ice layer
x_a is the width of the air layer
d is the depth of the plates

ε_{ri} = 90
ε_{ra} = 1

Since ε_{ri} of ice is much greater than ε_{ra} of air a good approximation for the capacitance of figure 2 can be made by ignoring the portion of the capacitor which is air-filled. Using this, equation (2) reduces to:

$$C = \varepsilon_{ri}\varepsilon_0 x_i d/g \qquad (3)$$

Equation (3) is linear with respect to the thickness of the ice, x_i, and the capacitance increases until the gap between the plates is filled. It is noted that filling the space out of the gap with ice will not increase the capacitance further.

The parallel plate capacitor is helpful in understanding the principles behind capacitive ice sensing but in a practical sense it would be better if the plates of the capacitor were coplanar, then the ice could build up on a flat surface. The flat plate capacitor is shown in figure 3.

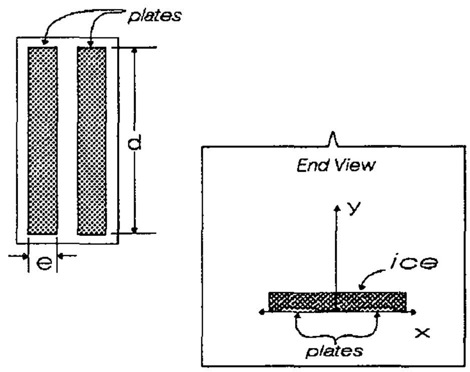


Figure 3

It is illustrative to transform the flat plate capacitor into a parallel plate capacitor using a complex conformal map. For an explanation of conformal mapping the reader is referred to "Complex Variables and Applications" Brown and Churchill, McGraw-Hill[2]. The conformal map chosen is:

$$w = \sin^{-1}(2z/g)$$

where: z is the complex number x + jy
w is the complex number u + jv
g is the gap between the plates
e is the width of a plate

let $e = k \cdot g$ where k is a constant

then the flat plate capacitor transforms into the parallel plate capacitor shown in figure 4.

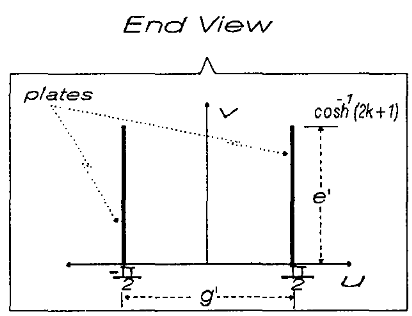


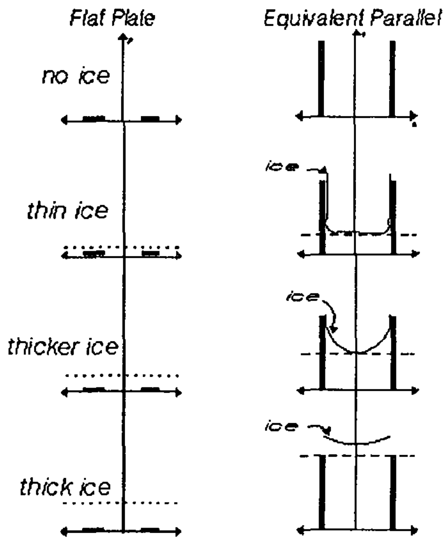
Figure 4

Next consider the case when a uniform layer of ice covers the probe. In figure 3 this corresponds to the complex number z = x + jc where c is a constant. Using the same conformal mapping as before, this transforms the ice layer into:

$$u = \operatorname{asin}\left[\frac{2}{g^2}\cdot\sqrt{\left(x+\frac{g}{2}\right)^2+c^2}-\sqrt{\left(x-\frac{g}{2}\right)^2+c^2}\right]$$

$$v = \operatorname{asinh}\left(2\cdot\frac{c}{g\cdot\cos(u)}\right)$$

Where u and v are, respectively, the real and imaginary components of the complex number w. The effect of ice of varying thicknesses is shown in figure 5.



(Note: Dashed lines are equivalent parallel ice depth)

Figure 5

It can now be noted that the capacitance of the flat plate capacitor can be approximated by the equivalent parallel plate capacitor for the depth of the area in the capacitor which is totally filled with ice. The area which is not totally filled with ice has a lower capacitance than if it were filled with air and can be safely disregarded.

Note that the thickness of the ice for which the capacitor changes linearly is about the same as the width of the gap between the plates and this is used as a rule of thumb for designing the capacitors for icing probes.

B. Practical Design Considerations

Requirements

Using the techniques described above, an ice sensing system consists of a capacitive probe, conditioning and measurement electronics, and user outputs. The system works by allowing the probe to gather ice, determining if the ice is thick enough to warrant releasing propane, then deicing the probe and beginning the process over again. The probe is heated to shed the ice. The probe must shed both the ice and the melt water during deicing since any residual water remaining on the probe will adversely effect the next measurement.

It should be noted that the plates on the probe cannot be coated with any insulative protective coating. If the plates are coated then the probe behaves as if there is no ice coating. The plates could be thinly coated with a metal whose oxide is conductive. Silver is such a metal.

Since the probe may be used in high winds the probe must be shaped so that it can collect ice in all directions.

Therefore, the practical capacitance probe has to:

1) Use energy efficiently to rapidly shed ice during the heating cycle.
2) Shed both ice and melt water during the heating cycle.
3) Have non-corroding/non-oxidizing plates.
4) Be shaped so that it can gather ice omni-directionally.

Prototype Probes

Initial testing of this concept was done using aluminum strips glued onto a glass plate. The capacitor was then coated with ice and the change of capacitance measured. The results were consistent with the theory described in the paper. Currently, three icing probes have been designed to be tested in winter 1996/1997.

Flat Plate Probe

The first and simplest prototype is the flat plate probe with back heating. The plates of the probe are etched from double sided printed circuit board material with the back of the probe being a solid sheet of copper. A foil heater is bounded to the back of the probe. This probe was constructed for proof of concept only since it is not omnidirectional.

Cylindrical Probe

The second probe is essentially many flat plate probes attached to the surface of a cylinder. The center of the cylinder contains the heating element. This probe is omnidirectional and easy to fabricate and if its water/ice shedding capabilities are adequate it would be the best probe design due to its simplicity, see figure 6.

Figure 6

Conical Probe

This probe is similar to the cylindrical probe but tapers to a point at the end. This probe will used if the ice shedding capabilities of the cylindrical probe prove to be inadequate, see figure 7.

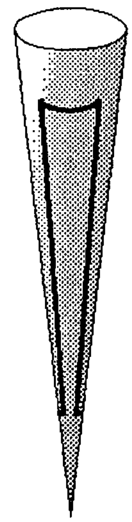


Figure 7

C. Advantages of Capacitive Ice Sensing

The ice sensing system described above has several distinct advantages. The probe design and contraction are simple with no moving parts. The probes are also rugged since they consist of metal plate or foil on an insulating substrate. Also, due to the simplicity of design the probes should be inexpensive to manufacture.

III CONCLUSION

Development of an ice sensing system using capacitive icing probes shows promise in that such a system may prove to be an inexpensive and reliable alternative to icing probes currently in use. Preliminary tests have given favorable results and have encouraged further capacitive probe/ice sensing system development. Development is now focused on probe shape and ice/melt water shedding capabilities.

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[1] Collins, M.P. and A.B. Super, 1984 and Boe, B., W. Hauze, and M.P. Collins, 1986: United States Bureau of Reclamation memos.
[2] Chapters 9 and 10 of the Sixth Edition, 1996.

"NON-REVIEWED"

AN APPLICATION OF HYGROSCOPIC FLARES
PHOTOGRAPHIC PAGE 1.

Photo 1, 1645: Looking toward Sierra crest at about 50° m.n. from camera site (3.109 m. msl) prior to seeding event.

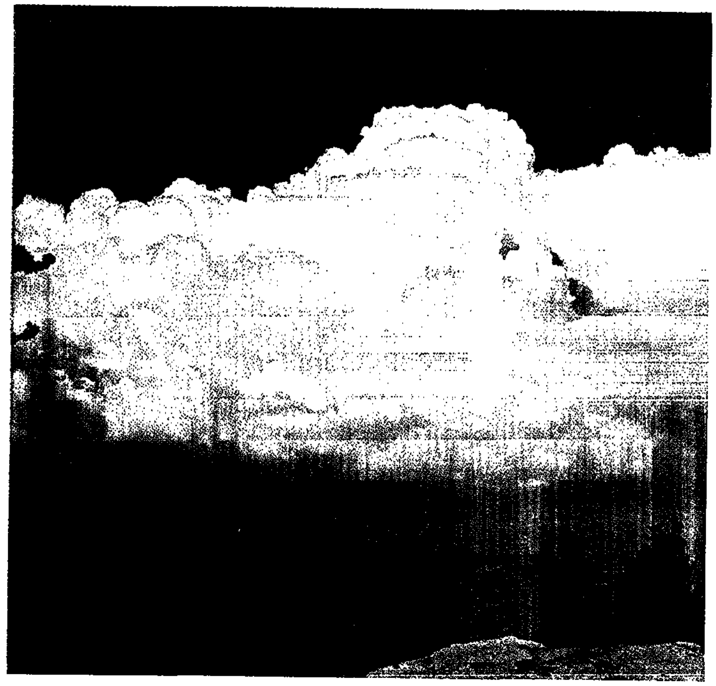

Photo 2, 1655: Small cumulus continue to grow. Seeding begins in updraft area at cloud base (center).

Photo 3, 1708: Eleven minutes after initial seeding with hygroscopic flares. Ice crystals in mid-cloud elevation.

Photo 4, 1722: Precipitation core is reaching ground level twenty-seven minutes after start of hygroscopic seeding.

AN APPLICATION OF HYGROSCOPIC FLARES - A SINGLE CASE STUDY

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ABSTRACT

A case study is presented here of seeding a single cumulus cell with hygroscopic flares. The test took place on 31 July 1996 over a section of the South Fork of the San Joaquin River in the Sierra Range of California. A 5 cm radar system focused on the area noted that the seeded cell grew to higher altitudes, produced a more intense precipitation echo, and lasted longer than any of the non-seeded cumulus cells growing simultaneously in adjacent areas. As previously observed in several hygroscopic flare applications, it was confirmed again that, in addition to rain, abundant amounts of small graupel and clear hailstones were produced within the seeded cloud.

1.0 BACKGROUND

The science and technology of hygroscopic materials to modify droplet spectra has been an important part of weather modification concepts for more than fifty years. In 1940 the development and field application of these materials were focused on the production of smokes and relevant generators. In more recent years the interest has moved toward the use of hygroscopic compositions for dissipating warm fogs and augmenting precipitation from both cold and warm cloud systems.

It would be nearly impossible to trace the complete lineage of hygroscopic particle production and types of generators because much of the initial work was a part of classified government investigations within the design of improved gas masks for the military, as well as production of screening smokes. It is enough to mention that during the period October 1940 through February 1944, scientists at the General Electric Research Laboratory in Schenectedy, New York, formed one of several groups which conducted a series of investigations with smoke, gas masks and filters under contract with the Office of Scientific Research and Development (GE Research, 1944). Fortuitously, scientists working at GE Research included Dr. Irving Langmuir and Vincent Schaefer who ultimately were two of the primary players in the discovery of materials and applications now used worldwide in cloud modification programs. During these investigations on producing white screening smokes, Langmuir and Schaefer developed methods of controlling particle sizes. As the particles grew, they found the growth rates could be stopped at any desired point. Methods followed which surprisingly produced very small particles of extraordinarily uniform sizes. In early 1947, Dr. Bernard Vonnegut, another team member, discovered silver iodide as an effective ice nucleus. The GE Research techniques for producing hygroscopic aerosols by vaporization and subsequent condensation were applied by Vonnegut (Vonnegut, B., 1947) in the design of various prototype generators to produce silver iodide as submicron particles. Models based on these prototypes are used in present cold cloud seeding programs throughout the world.

For the next several years, research in the production of hygroscopic particles was essentially dormant. In the 1960s, specific field tests were conducted on the production of condensation nuclei smoke particles and the effects of pyrotechnic seeding devices (Henderson, 1962; Henderson, 1963). Further interest was regenerated by the Naval Weapons Center (NWC) at China Lake, California. Applications were developed to produce large numbers of cloud droplets at 75% relative humidity (Blomerth, et al., 1970). Field observations and measurements noted particles from paper mills and their effect on clouds and precipi-

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