Using Multiphysics for Detecting Atmospheric Ice Through MuVi Graphene – Atmospheric Icing Sensor

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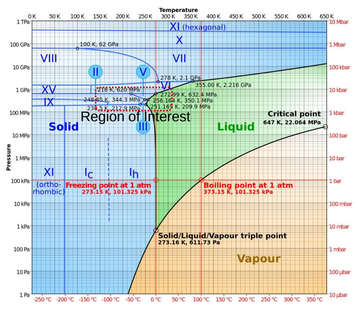
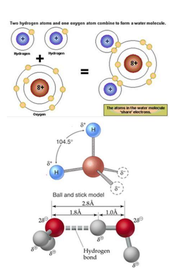
1. Introduction

- Background study of existing atmospheric ice sensing techniques .
- Understanding atmospheric ice and its physical and chemical properties
- Understanding analytical and numerical methodologies to design a modular, innovative robust sensory solution

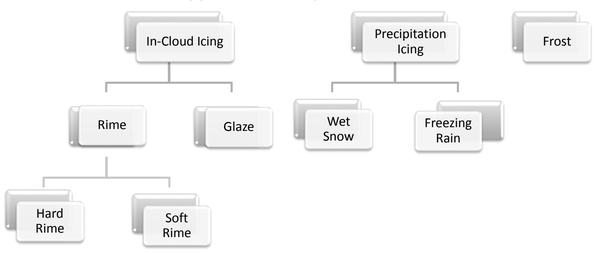
Phase Diagrame of Water



Water Molecule



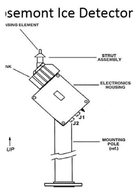
Types of atmospheric ice



2. Existing Atmospheric Ice Sensing Techniques

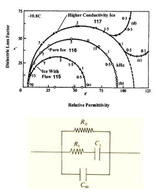
Patents	Potential Capability				
	Ice Detection	Ice Type	Ice Thickness	Icing Rate	Icing Load
Capacitive Based Technique					
Ice Sensor by Weinstein	✓		✓		
Ice Sensor by Kwadwo	✓	✓	✓		
Ice Sensor by Jarvinene	✓	✓	✓	✓	
Ultrasonic Based Technique					
Ice Sensor by Luukkala	✓				
Ice Sensor by Watkins	✓				
Resonance Based Technique					
Ice Sensor by Cronin	✓				
Ice Sensor by Koosman	✓				
Microwave Based Technique					
Ice Sensor by Overall	✓				
Ice Sensor by Magenheim	✓				✓
Impedance Based Technique					
Ice Sensor by Seegmiller	✓				✓
Ice Sensor by Wallace	✓				
Infrared Based Technique					
HoloOptic Sensor	✓			✓	
Load Cell Based Technique					
Ice Meter					✓
Ice Moniter					✓
Hybrid Technique					
MuVi-Graphene by HiN (In-Progress)	✓	✓	✓	✓	✓

Isemont Ice Detector

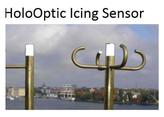


Ice Load Monitor

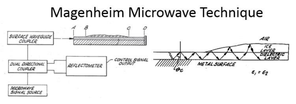
Jarvenin Capacitive Technique



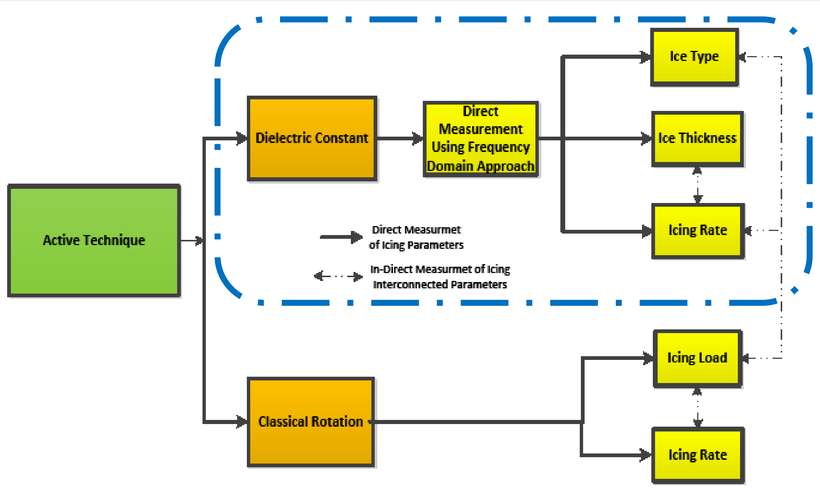
HoloOptic Icing Sensor



Magenheim Microwave Technique

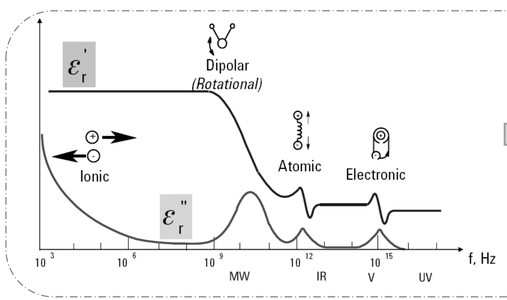


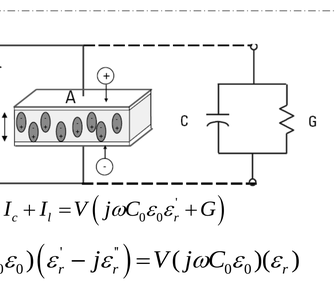
3. Methodology



4. Analytical Understanding

Dielectric Measurement

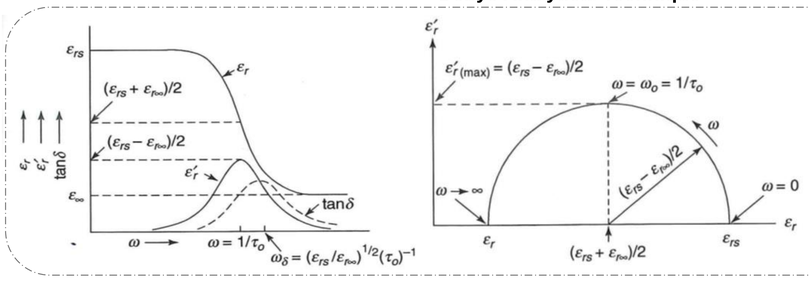




$$I = I_c + I_l = V\left(j\omega C_0 \varepsilon_0 \varepsilon_r^{'} + G\right)$$

$$I = V(j\omega C_0 \varepsilon_0)\left(\varepsilon_r^{'} - j\varepsilon_r^{''}\right) = V(j\omega C_0 \varepsilon_0)(\varepsilon_r)$$

Debye Analytical Technique



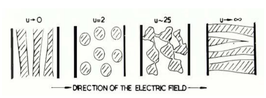
$$\varepsilon_r^{'} = \varepsilon_{r\infty} + \frac{\varepsilon_{rs} + \varepsilon_{r\infty}}{1 + \omega^2 \tau_\circ^2}$$

$$\varepsilon_r^{''} = \frac{\left(\varepsilon_{rs} - \varepsilon_{r\infty}\right)\omega\tau_\circ}{1 + \omega^2 \tau_\circ^2}$$

$$\tan\delta = \frac{\varepsilon_r^{''}}{\varepsilon_r^{'}} = \frac{\left(\varepsilon_{rs} - \varepsilon_{r\infty}\right)\omega\tau_\circ}{\varepsilon_{rs} + \varepsilon_{r\infty}\omega^2\tau_\circ^2}$$

Dielectric Relations For Atmospheric Ice

$$\frac{\varepsilon_m - 1}{\varepsilon_m + u} = (\rho)\frac{\varepsilon_1 - 1}{\varepsilon_1 + u} + (1-\rho)\frac{\varepsilon_2 - 1}{\varepsilon_2 + u}$$



$$\varepsilon_d^{'} = \frac{\left(\rho u - u - \rho u\varepsilon_{ice}^{'} - \varepsilon_{ice}^{'}\right)\left(\rho\varepsilon_{ice}^{'} - \rho - u - \varepsilon_{ice}^{'}\right) - \left(\rho\varepsilon_{ice}^{''} - \varepsilon_{ice}^{''}\right)\left(\rho u\varepsilon_{ice}^{''} + \varepsilon_{ice}^{''}\right)}{\left(\rho\varepsilon_{ice}^{'} - \rho - u - \varepsilon_{ice}^{'}\right)^2 + \left(\rho\varepsilon_{ice}^{''} + \varepsilon_{ice}^{''}\right)^2}$$

$$\varepsilon_d^{''} = \frac{-\left(\rho u - u - \rho u\varepsilon_{ice}^{'} - \varepsilon_{ice}^{'}\right)\left(\rho\varepsilon_{ice}^{''} - \varepsilon_{ice}^{''}\right) - \left(\rho\varepsilon_{ice}^{'} - \rho - u - \varepsilon_{ice}^{'}\right)\left(\rho u\varepsilon_{ice}^{''} + \varepsilon_{ice}^{''}\right)}{\left(\rho\varepsilon_{ice}^{'} - \rho - u - \varepsilon_{ice}^{'}\right)^2 + \left(\rho\varepsilon_{ice}^{''} - \varepsilon_{ice}^{''}\right)^2}$$

'ε_m' is the dielectric constant of the mixture,
'ε_1' and 'ε_2' are the dielectric constants of two materials,
'ρ' is the proportion of the total volume occupied by medium '1',
u is the Formzahl number

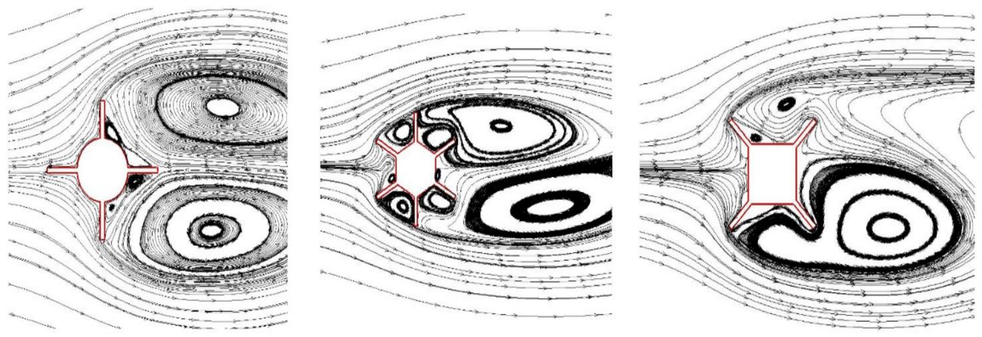
Mathematical Modeling of Conductivity

$$\sigma(\omega) = \sigma_0 + A\omega^n$$

$$\sigma(\omega, T) = \sigma_s(T) + \left(\sigma_\infty(T) - \sigma_s(T)\right)\left(\frac{\omega}{\omega_p}\right)^{\frac{T - T_{cuttoff\,1}}{T_{cuttoff\,2} - T_{cuttoff\,1}}}$$

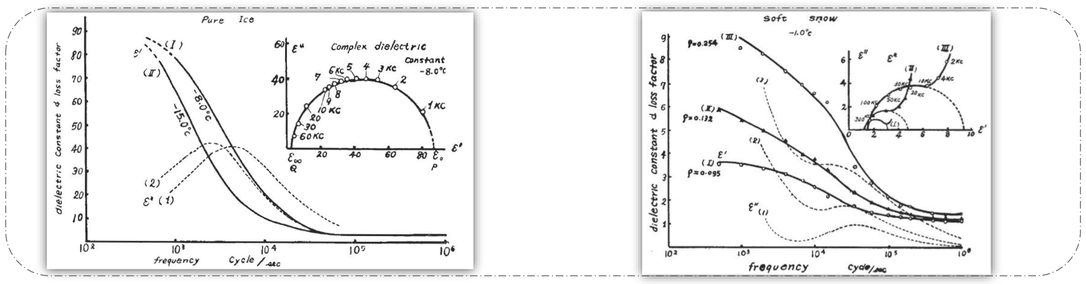
5. Prospective Design Options- CFD

Velocity streamlines, v = 10 m/s

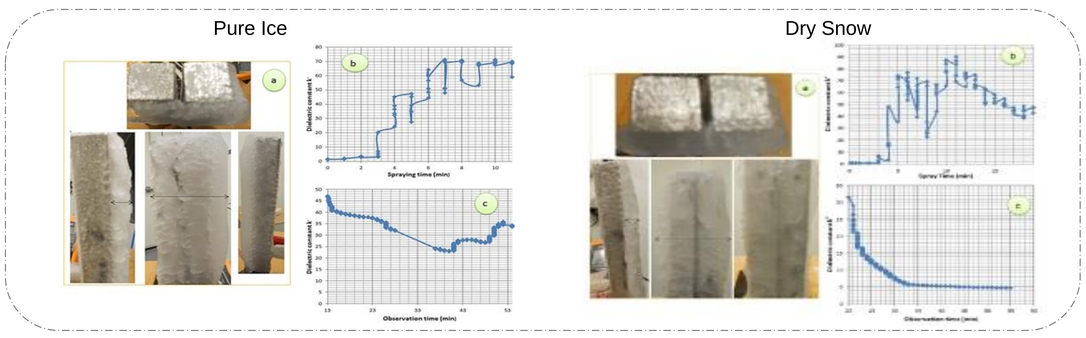


6. Analytical, Experimental and Numerical Comparisions

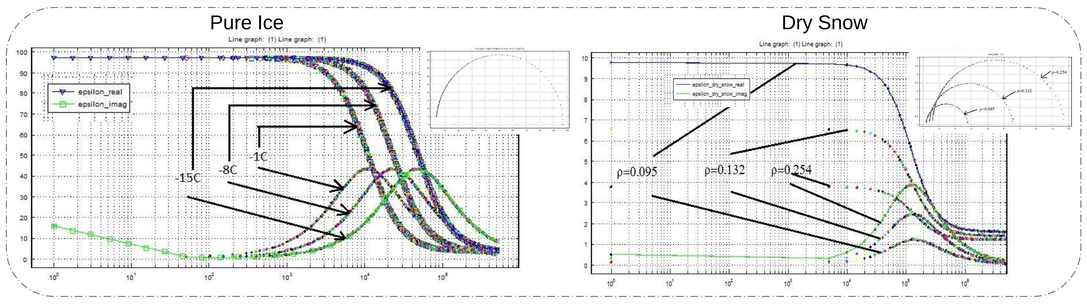
Dielectric Variations in Atmospheric Ice -Experimental Results of Kuroiwa



Dielectric Variations in Atmospheric Ice -Experimental Results in Cold Room Chamber

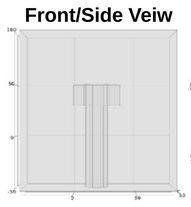


Dielectric Variations in Atmospheric Ice –Numerical Results in Comsol

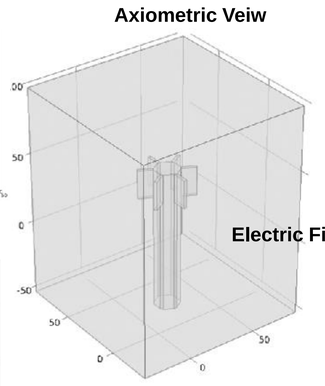


7. MuVi Graphene Preliminary Design

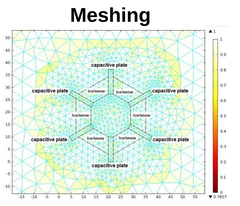
Front/Side Veiw



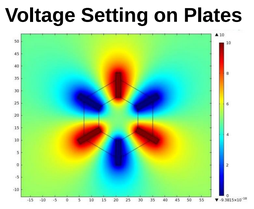
Axiometric Veiw



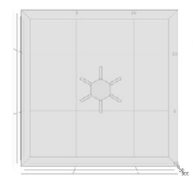
Meshing



Voltage Setting on Plates



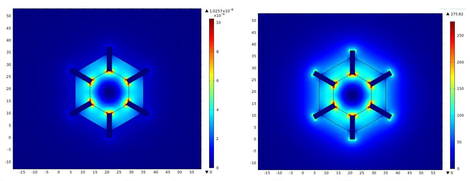
Top Veiw



Electric Field and Displacement Field Norm on Atmospheric Ice

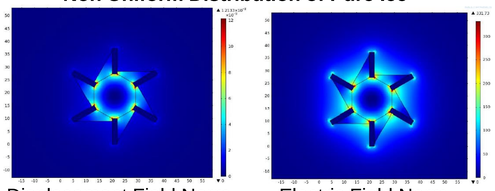
Atmospheric Ice	Multiphysics Variables	
	Electric Field Norm	Displacment Field Norm
Pure Ice	147.7	5.49×10^{-9}
Dry Snow, ρ = 0.8	152.63	3.88×10^{-9}
Dry Snow, ρ = 0.4	156.6	2.76×10^{-9}

Uniform Distribution of Pure Ice



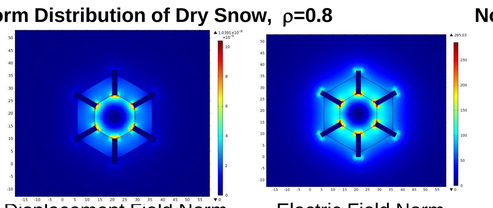
Displacement Field Norm | Electric Field Norm

Non Uniform Distribution of Pure Ice



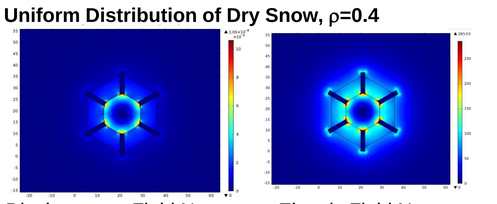
Displacement Field Norm | Electric Field Norm

Uniform Distribution of Dry Snow, ρ=0.8



Displacement Field Norm | Electric Field Norm

Non Uniform Distribution of Dry Snow, ρ=0.4



Displacement Field Norm | Electric Field Norm

8. Results

- A prototype hybrid atmospheric icing sensor MuVi-Graphene can possibly have adequate potential to detect icing, icing type, melting rate, icing load and icing rate.
- Debye Model used to model the permittivity variations to detect an atmospheric icing event and icing type.
- Modifiied Conductivity Relation is used to model the conductivity variations as a function of excitation frequency and temperature.
- Preliminary Geometrical Understanding and Analysis of MuVi Graphene were done using Multiphysics Solver (Comsol).

Excerpt from the proceedings of the 2015 COMSOL Conference in Grenoble

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