MuVi
A Hybrid Prototype of Atmospheric Icing Sensor

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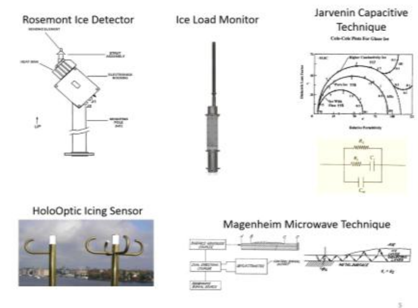
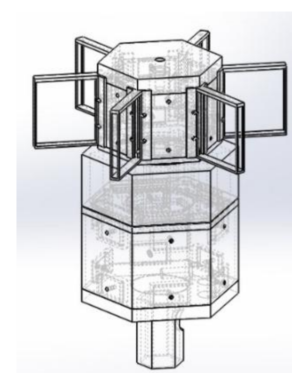
29 June – 3 July, IWAIS 2015, Uppsala, Sweden

My Today’s Talk Will Comprise

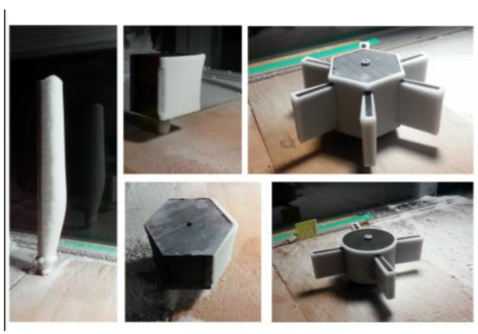
Motivation/Need



Available Sensors for Atmospheric Ice



1st Prototype Design

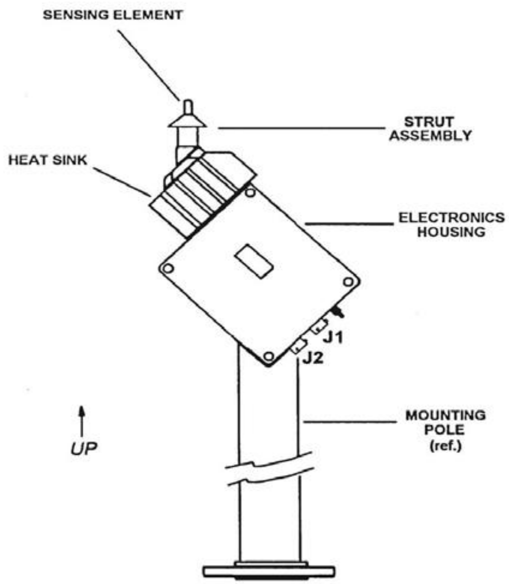


Testing

Motivation

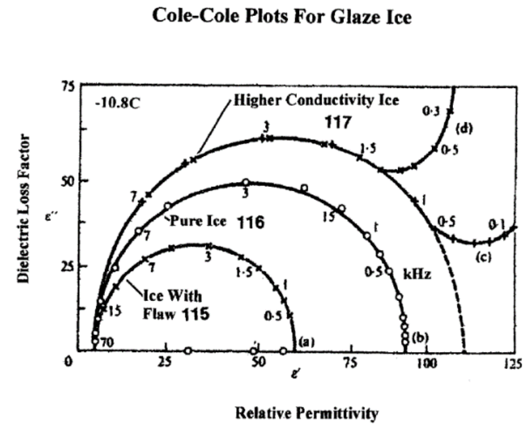
- Atmospheric ice effects
  - Static loads
  - Dynamic loads
  - Wind interaction with iced structures
- Critical parameters for de icing and anti icing
  - Ice thickness
  - Ice deposition rate
  - Ice type
  - Ice load
  - Melting rate
- Problem with present sensing techniques
  - Loading errors
  - ***Multifunctionality***
  - Redundancy
  - Robustness
  - Point devices

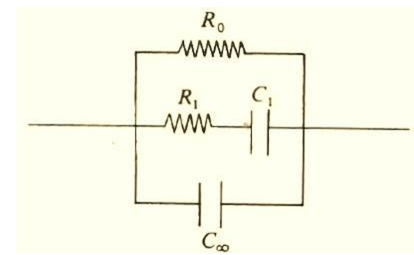
Rosemont Ice Detector



Ice Load Monitor

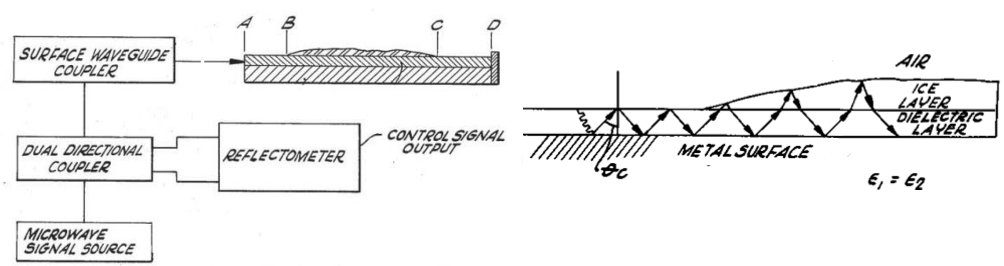
Jarvenin Capacitive Technique





HoloOptic Icing Sensor

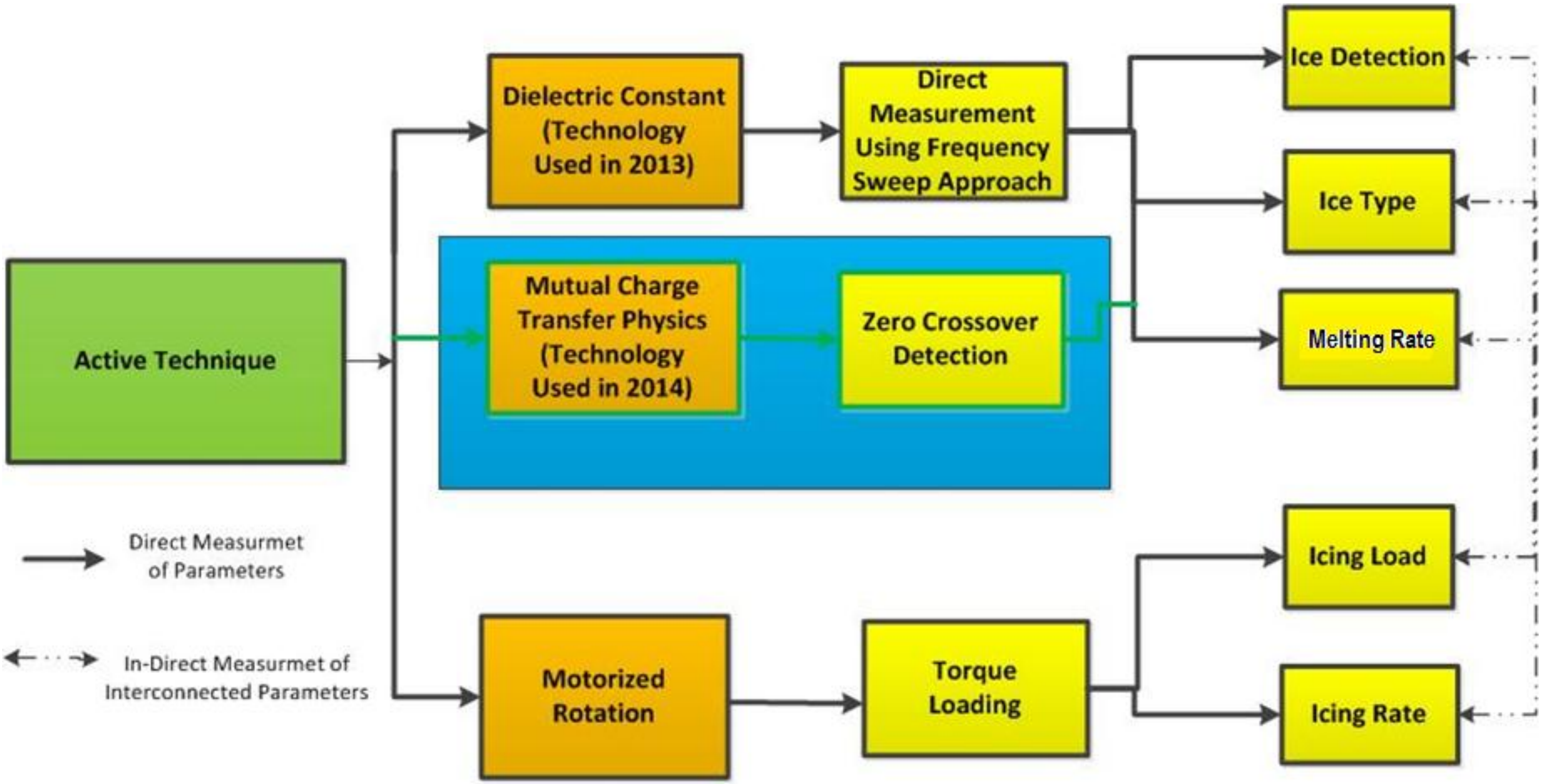
Magenheim Microwave Technique



Patents/Available Sensors	Ice Detection	Ice Type	Ice Thickness	Icing Rate	Ice Load
Capacitive Based Techniques					
Ice sensor by Weinstein	X		X		
Ice sensor by Kwadwo	X	X	X		
Ice sensor by Jarvinen	X	X	X	X	
Ultrasonic Based Techniques					
Ice sensor by Luukkala	X				
Ice sensor by Watkins	X				
Resonance Based Techniques					
Ice sensor by Cronin	X				
Ice sensor by Koosmann	X				
Microwave Based Technique					
Ice sensor by Overall	X				
Ice sensor by Magenheim	X				
Impedance Based Techniques					
Ice sensor by Seegmiller	X		X		
Ice sensor by Wallace	X		X		
Infrared Based Technique					
Holo optic sensor	X	X		X	
Load cell Based Technique					
Ice Moniter	X			X	X
Ice Meter	X			X	X
Hybrid (Rotary Loading and Capacitive Loading)					
MuVi (prototype by NUC)	X	x	x	X	X

Conceptual Design

Proposed Skeleton



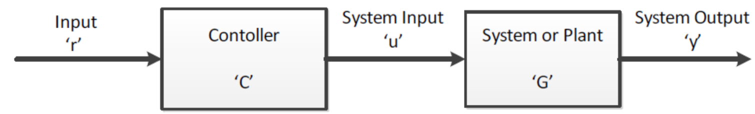
Achieving Adequate Rotational Loading for Icing Load

Motor Selection (Stepper or Servo)

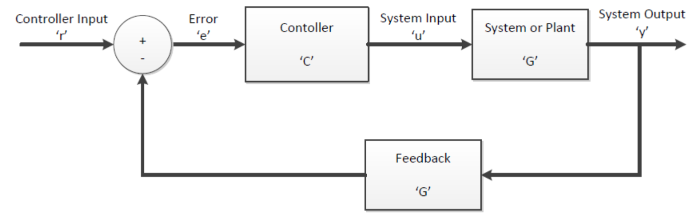
Advantages to use Stepper Motor

- Avoid complex steady state errors,
- Avoid stability problems
- Avoid Amplication of dynamic wind loads on iced structure
- No closed loop push/pull characteristics as like servo motor
- Possiblity to be in closed loop by an encoder
- More robust in Cold Climate

Open Loop Characteristics



Closed Loop Characteristics



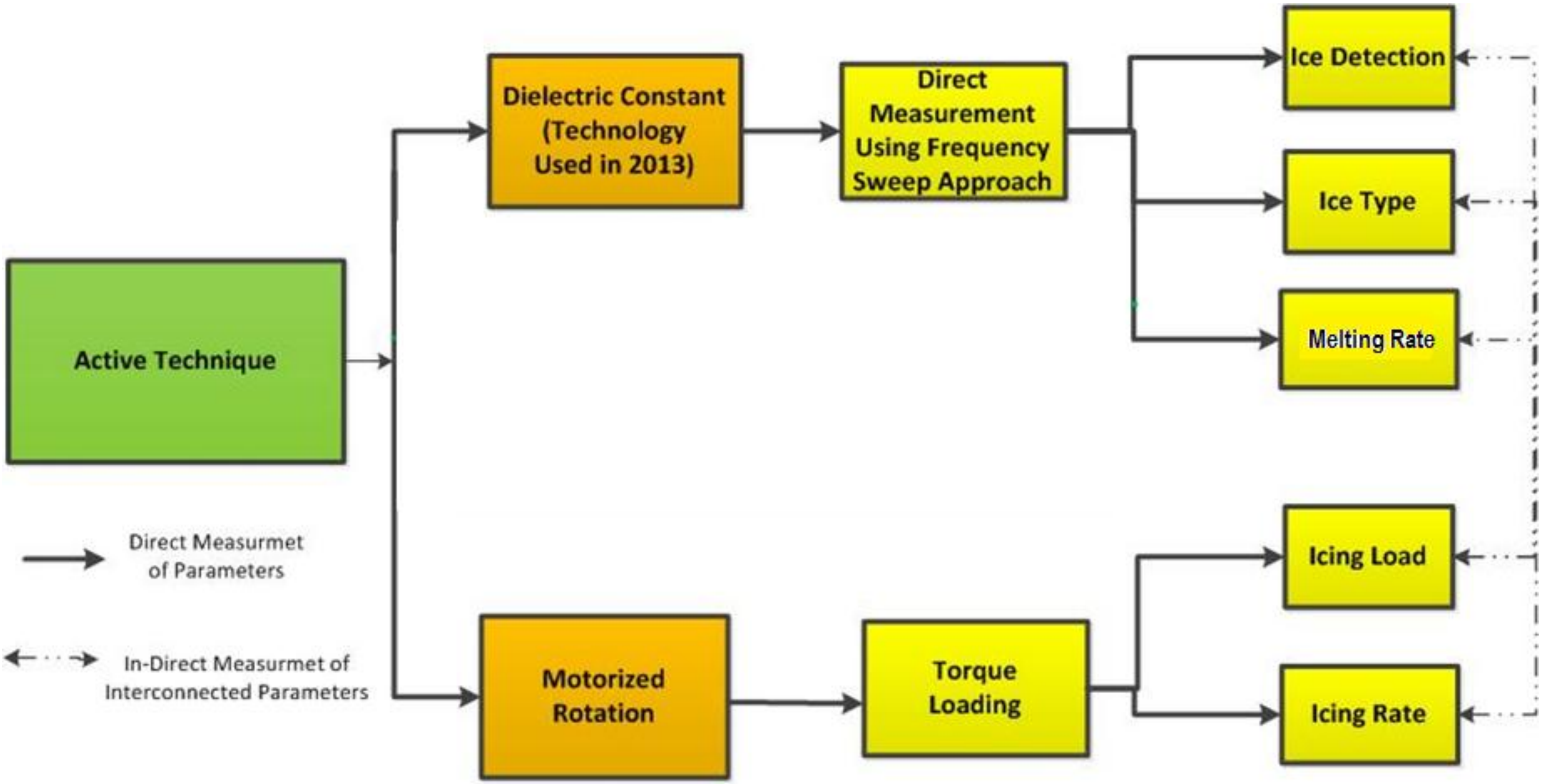
Mathematical Modeling

$$J = \frac{\alpha V_{in} I_{in} - \eta}{\beta \gamma \Omega_m^3} = aI_{in} - b$$

$$m_{ice} = \frac{a}{R_{ice}^2}\delta I_{in(ice)} + \frac{aI_{in} - J - b}{R_{ice}^2} = A\delta I_{in(ice)} + B$$

J-I Relation
m-I Relation

Proposed Skeleton



Debye Relations for the Parameters of Interest

$$\tau_0 = \tau_h e^{\frac{H}{kT}}$$

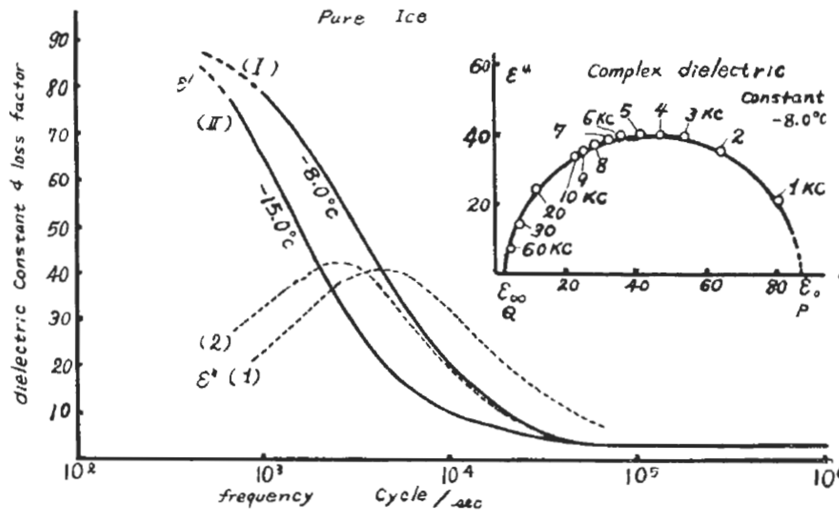
$$\varepsilon_r' = \varepsilon_{r\infty}^T + \frac{\varepsilon_{rs}^T + \varepsilon_{r\infty}^T}{1 + \omega^2 \tau_h^2 e^{\frac{2H}{kT}}}$$

$$\varepsilon_r'' = \frac{(\varepsilon_{rs}^T - \varepsilon_{r\infty}^T)\omega \tau_h e^{\frac{H}{kT}}}{1 + \omega^2 \tau_h^2 e^{\frac{2H}{kT}}}$$

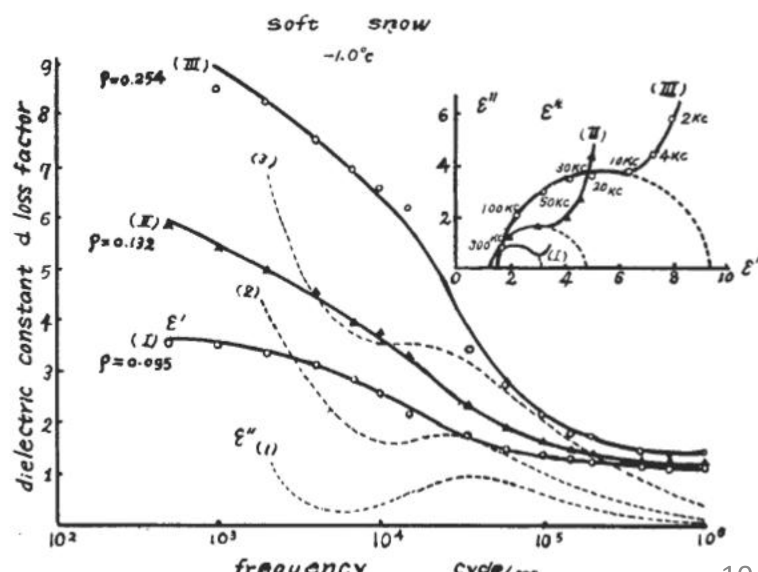
$\varepsilon_{r\infty}$ = Relative Permittivity at Very High Frequency
ε_{r0} = Relative Permittivity at DC Value
ω = Excitation Frequency
τ_0 = Relaxation time

ref : The dielectric properties of ice and snow Kuroiwa 1956

Dielectric constant of pure ice
(Experimental results)



Dielectric constant of soft snow

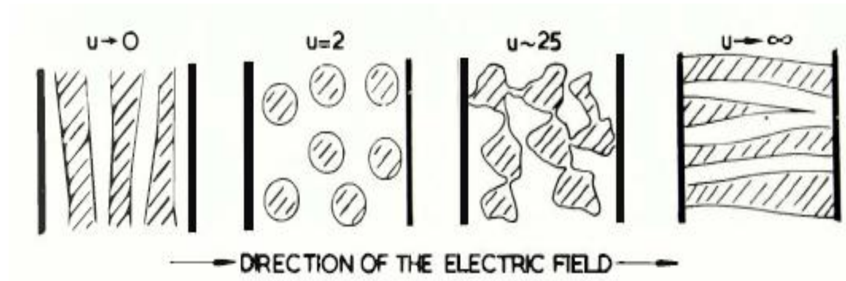


Dielectric Mixture Formulae

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

Wiener relation

'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



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

Atmospheric Ice Relation

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

Analytical Model - Conductivity Relation for Atmospheric Ice

Parameter	Value	Ref
C_∞ E_∞	$1.6\mathrm{x}10^{6}$ S/m 0.57 eV	[5]
σ_∞ (@ 0^0C, 10kHz) E_∞ (@ 0^0C, 10kHz)	$(4.47\pm0.14)\ \mathrm{x}10^{-5}$ S/m (0.56 ± 0.004) eV	[6]
σ_s (@ 10^0C) E_s (@ T > 40^0C)	$(1.1\pm0.5)\mathrm{x}10^{-8}$ S/m (0.34 ± 0.02) eV	[4]

UDR: Conductivity Relation

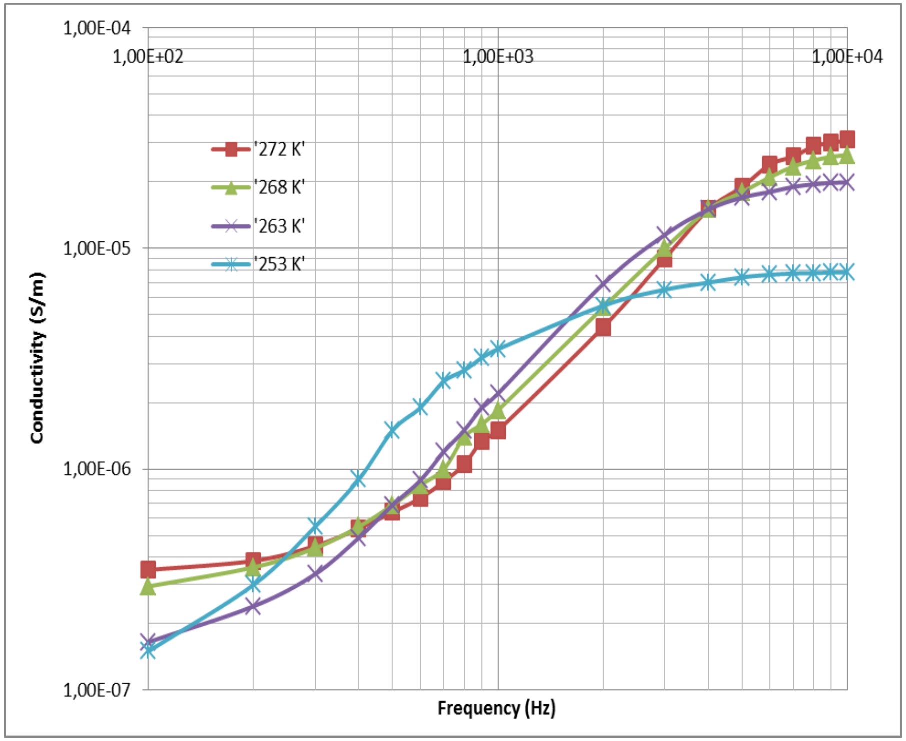
$$\sigma(\omega) = \sigma_0 + A\omega^n$$

However it is found that

$\sigma_0 = f(\sigma_s, \sigma_\infty)$

$A = g\ (\sigma_s, \sigma_\infty)$

$n = f(T) \quad [0,1]$



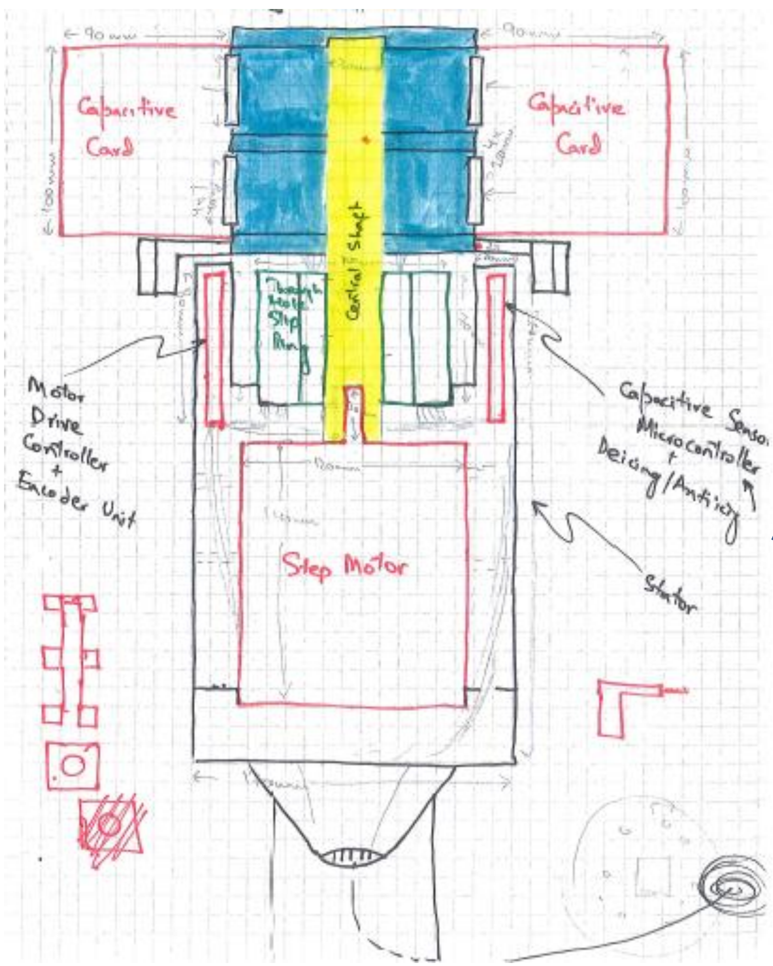
Experimental results of Fujino [10] for Conductivity variation with frequency and temperature for pure ice

Modified Conductivity Relation

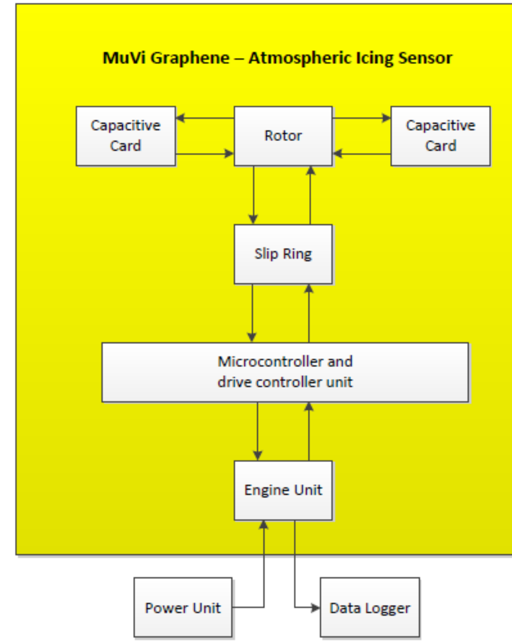
$$\sigma(\omega,T) = C_s e^{(-E_S/kT)} + \left(C_\infty e^{(-E_\infty/kT)} - C_s e^{(-E_S/kT)}\right)\left(\frac{\omega}{\omega_p}\right)^{\frac{T - T_{cuttoff\ 1}}{T_{cuttoff\ 2} - T_{cuttoff\ 1}}}$$

Preliminary Design

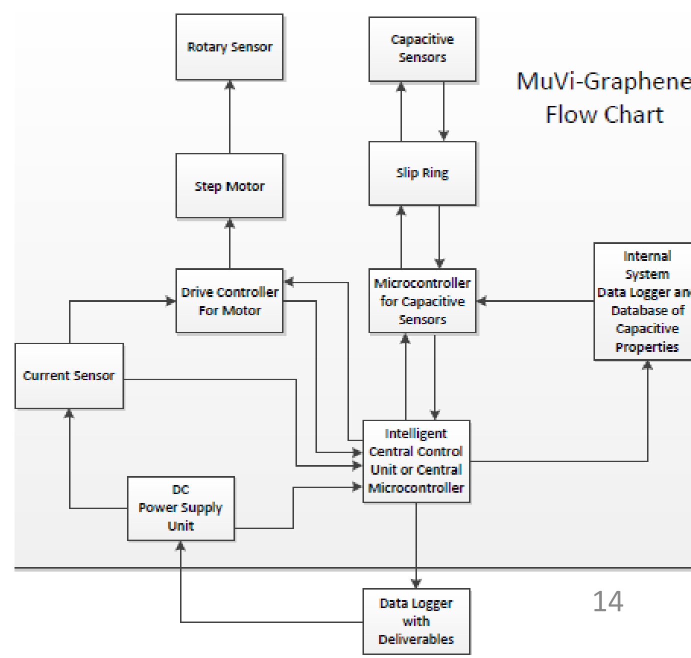
MuVi-Graphene Paper Sketch



MuVi Design Skeleton

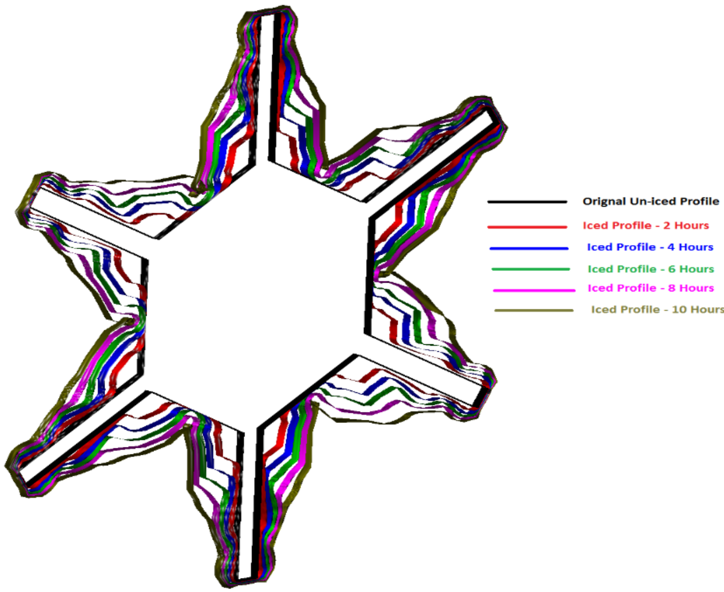


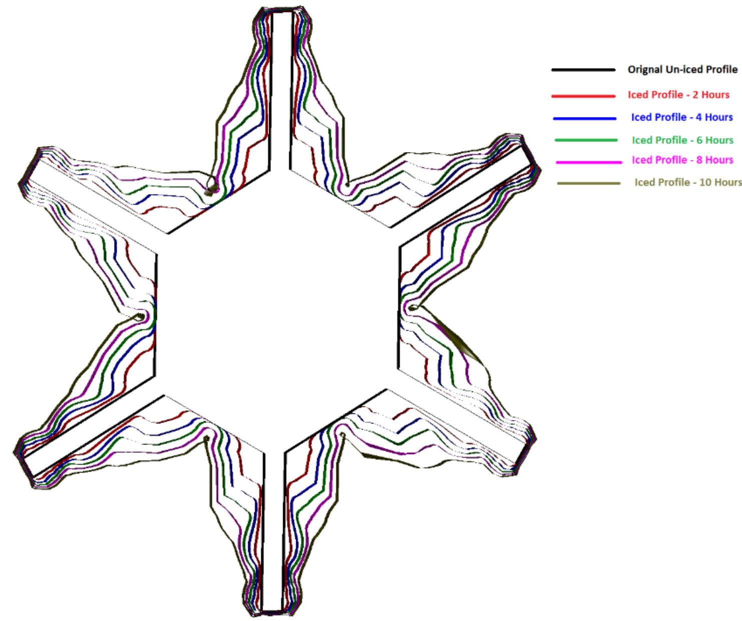
MuVi Working Principle

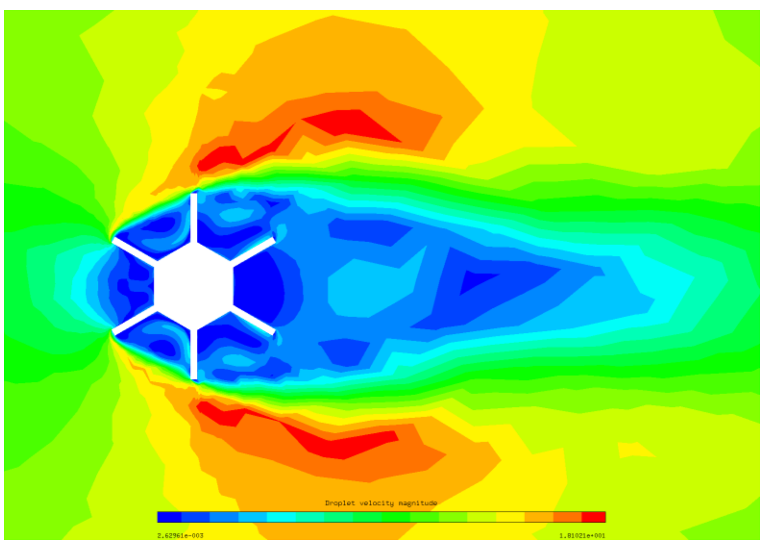


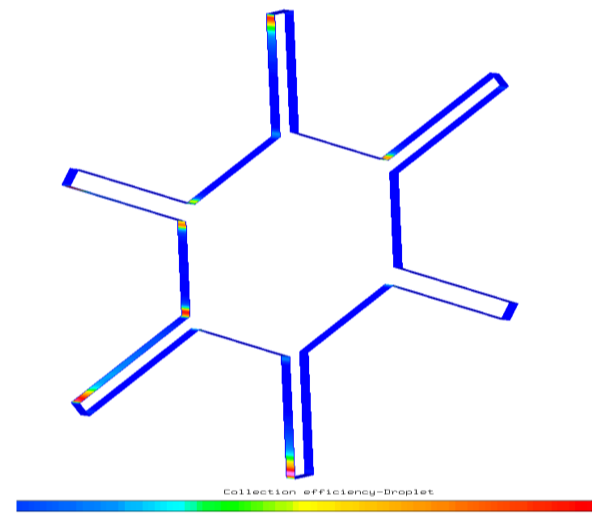
CFD Simulations of Atmospheric Ice on Rotating Hexagon with six capacitive plates

(10hours Simulation Time with Rime Ice)



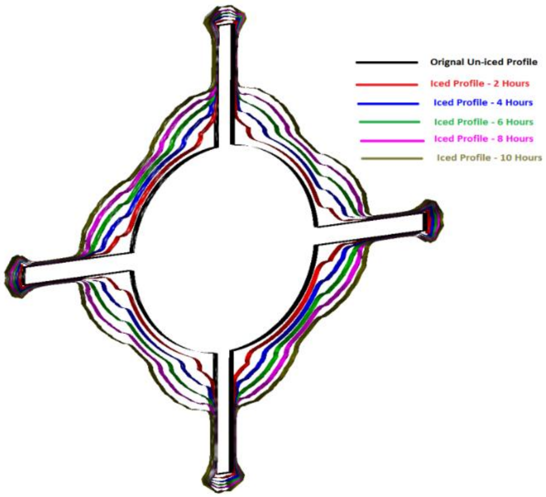


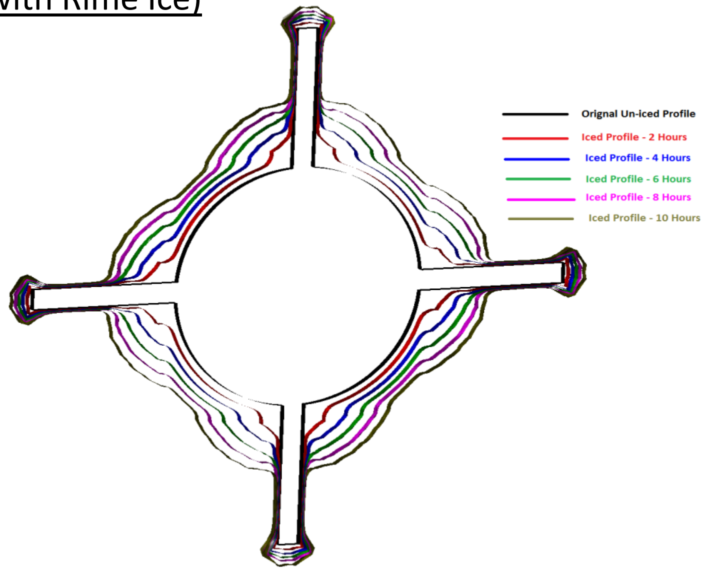


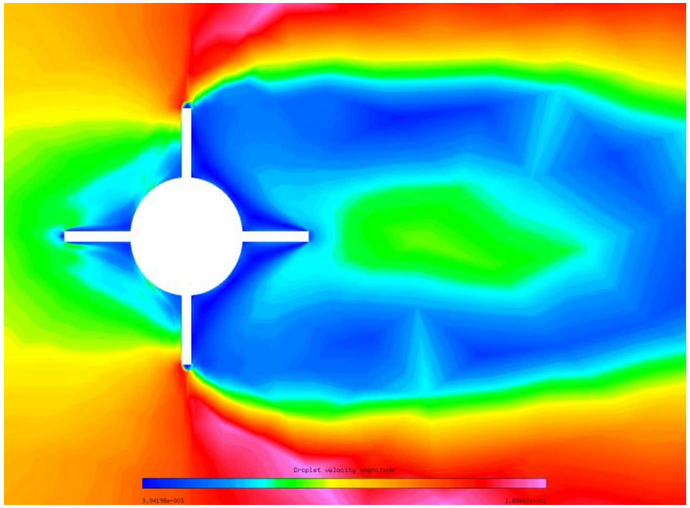


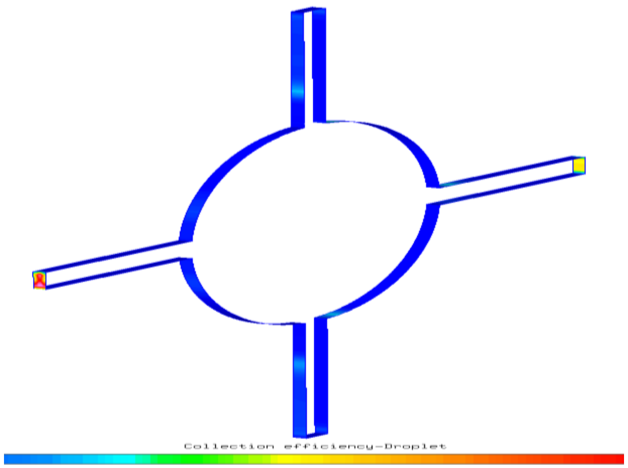
CFD Simulations of Atmospheric Ice on Rotating Circle with four capacitive plates

(10hours Simulation Time with Rime Ice)



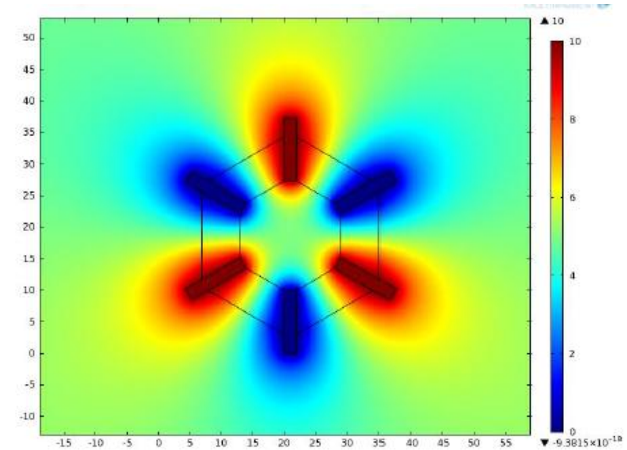




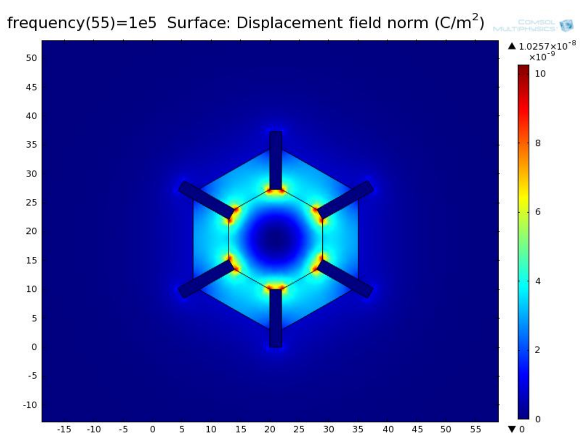


$$D = \varepsilon_0 \varepsilon_r E$$

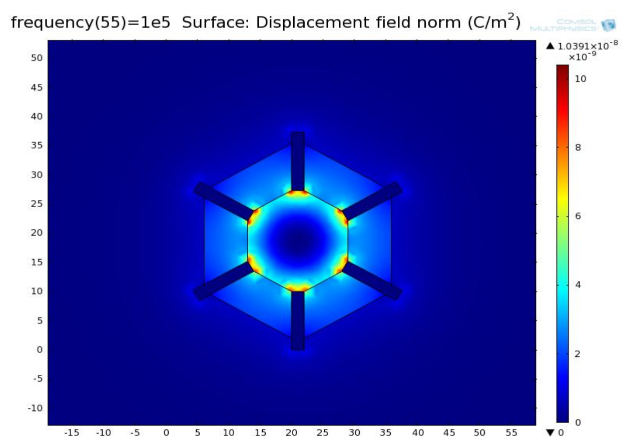
Atmospheric Ice Type	Electric Field Intensity [V/m]	Displacement Field [C/m²]
Glaze Ice	154	5.49×10^{-9}
Dry Snow ρ=0.8	154	3.88×10^{-9}
Dry Snow ρ=0.4	154	2.76×10^{-9}



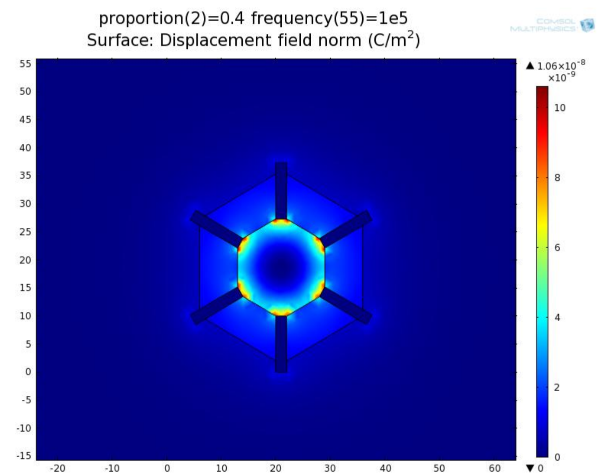
Glaze Ice



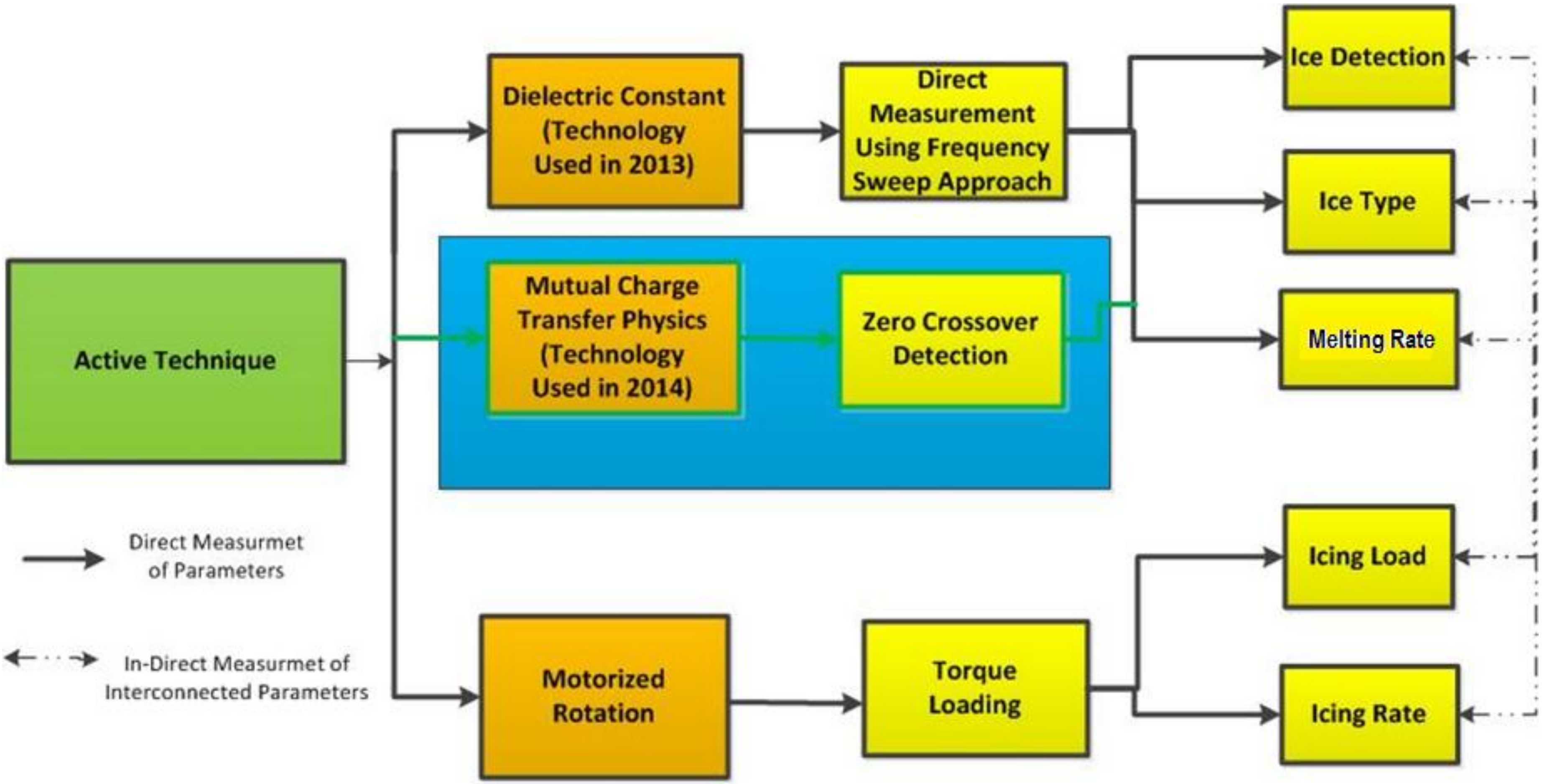
Dry Snow ρ=0.8



Dry Snow ρ=0.4



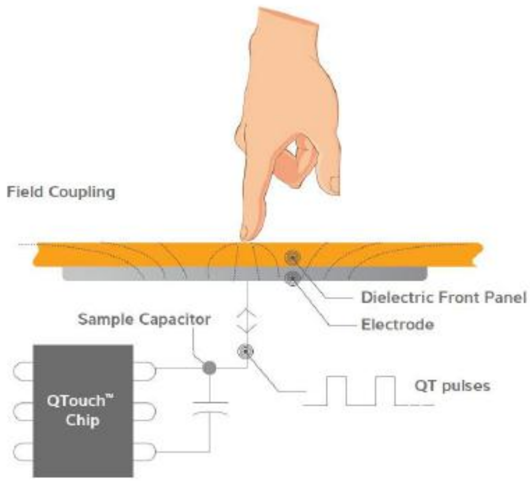
Proposed Skeleton

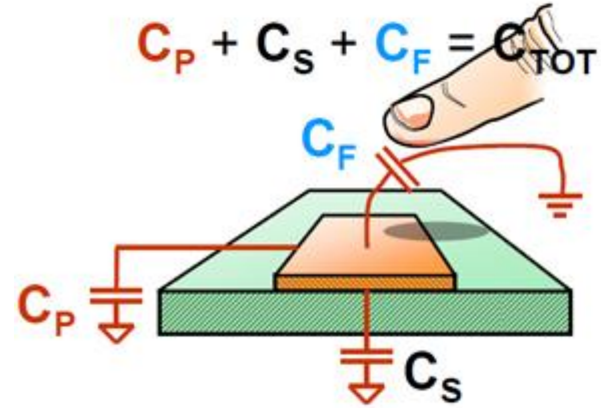


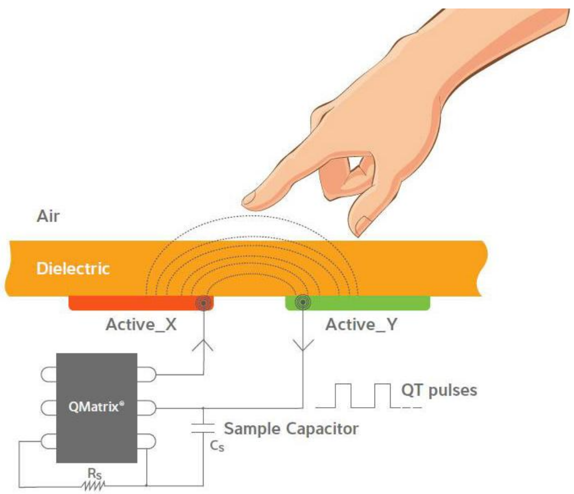
E – Driven Technology

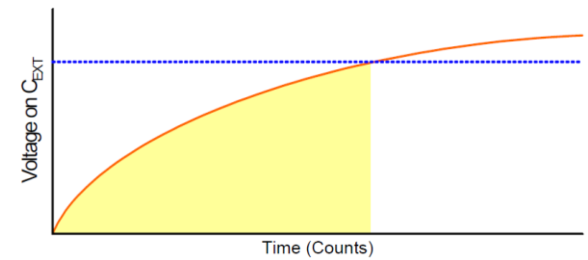
$$C = \varepsilon_r \varepsilon_0 \frac{A}{d}$$

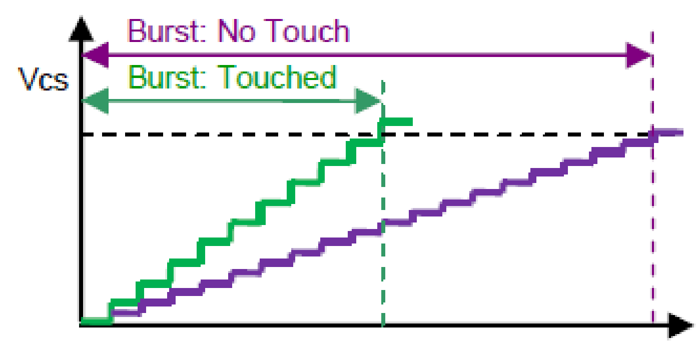
$$C_P + C_S + C_F = C_{TOT}$$



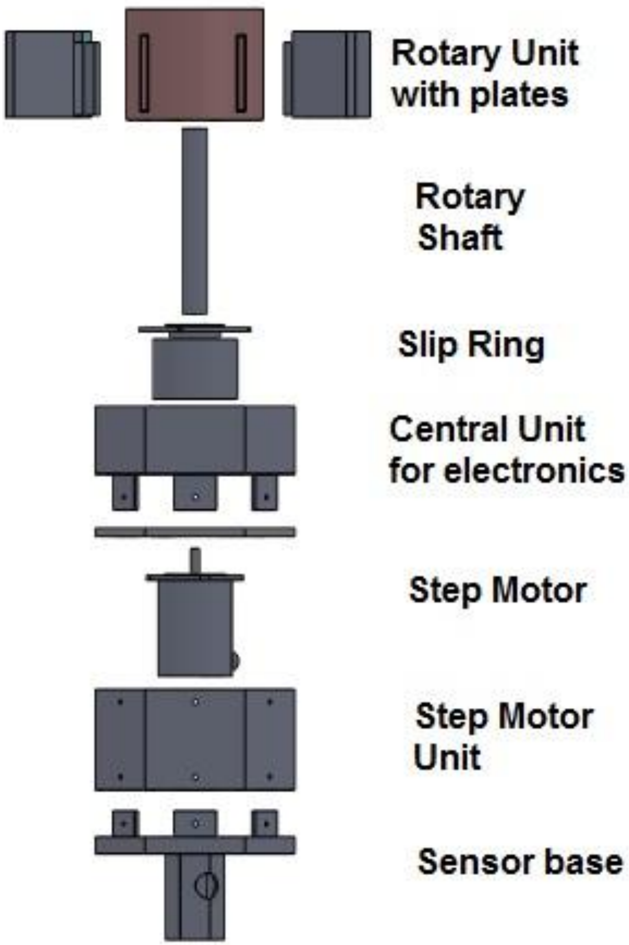


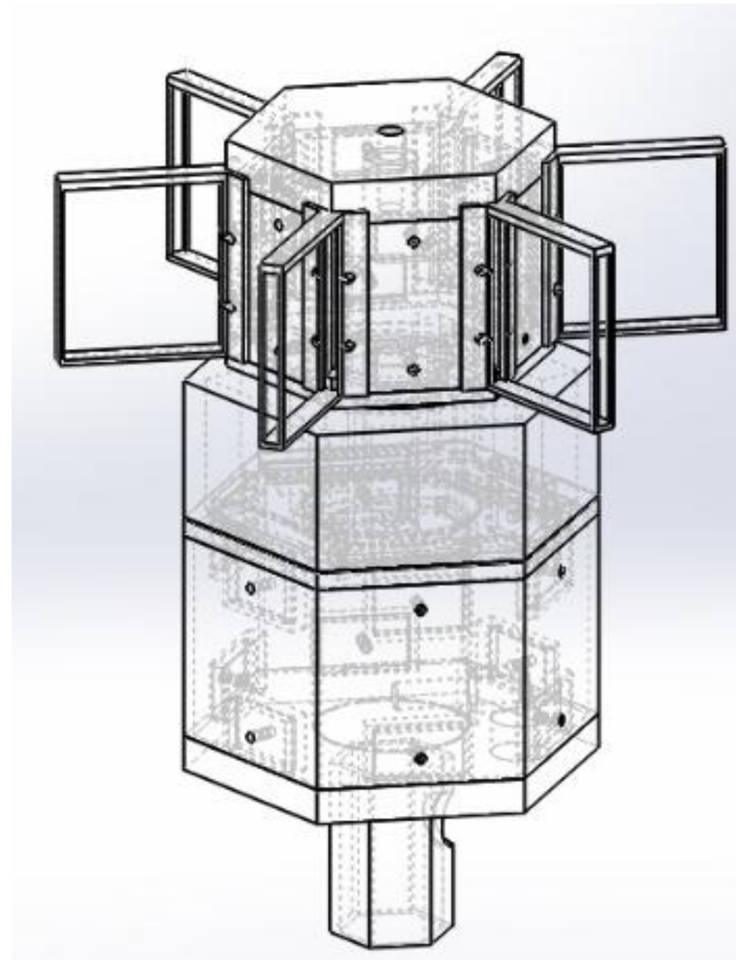


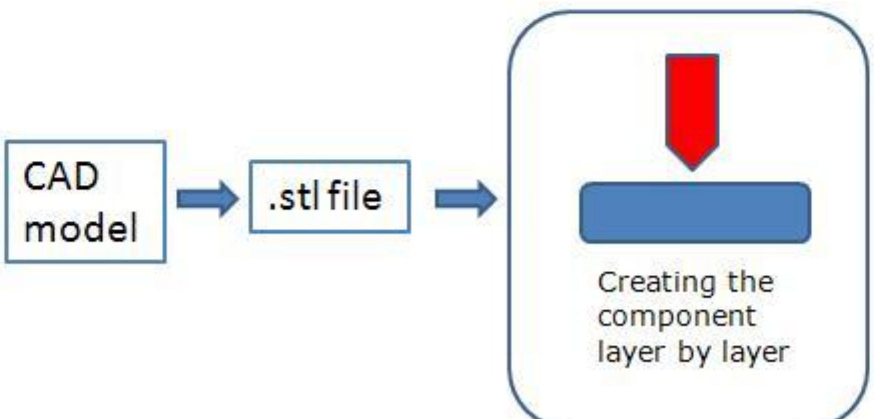


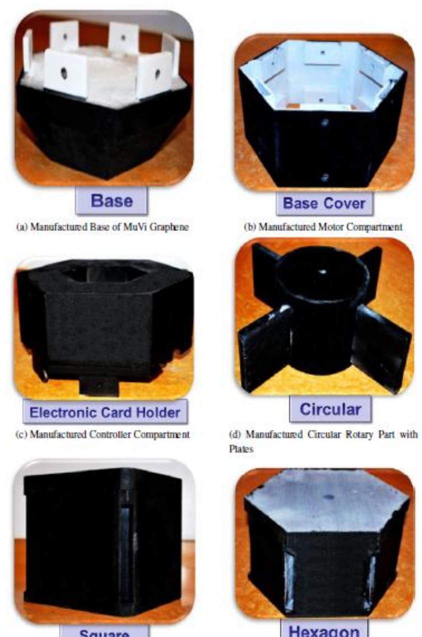


Detail Design


Rotary Unit
with plates
Rotary
Shaft
Slip Ring
Central Unit
for electronics
Step Motor
Step Motor
Unit
Sensor base







(a) Manufactured Base of MuVi Graphene

(b) Manufactured Motor Compartment

(c) Manufactured Controller Compartment

(d) Manufactured Circular Rotary Part with Plates

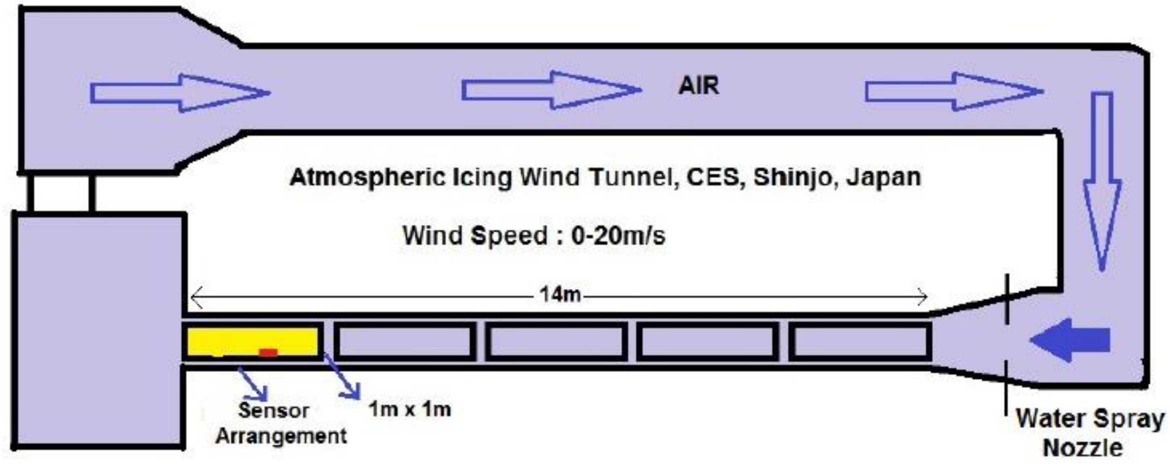
(e) Manufactured Rectangular Rotary Part

(f) Manufactured Hexagonal Prism Rotary

(a) Manufactured Shaft

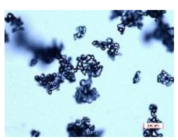
(b) Manufactured Complete Sensor with Circular Top

Experimentation

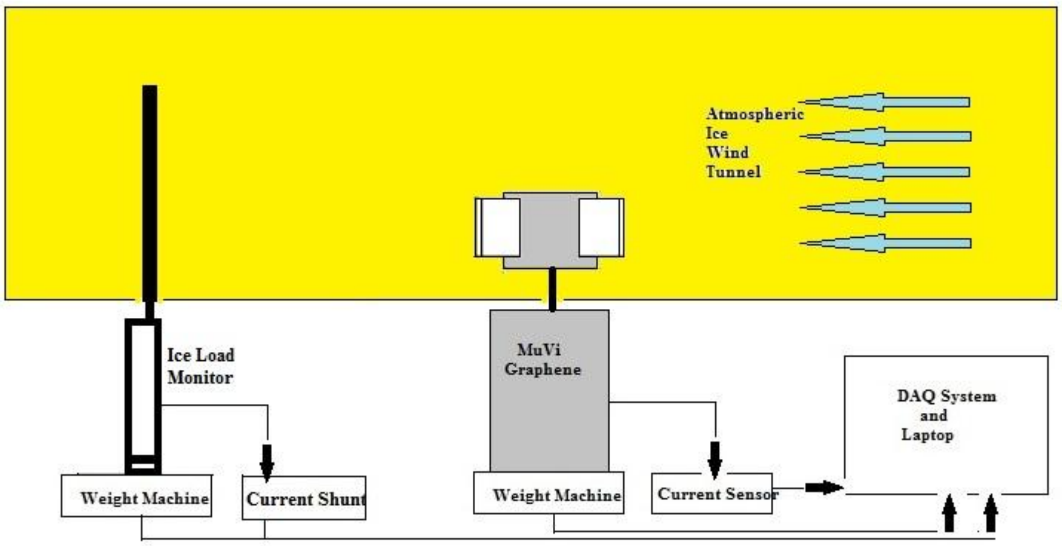


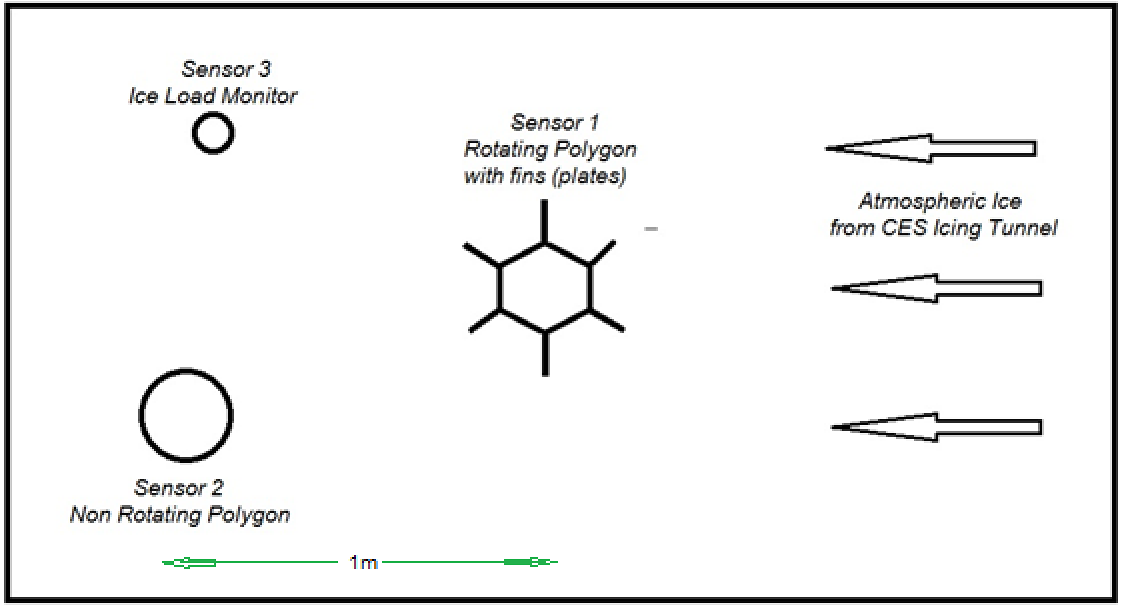
Cryospheric Environmental Simulator @ NIED, Shinjo, Japan

Cryospheric Environmental Simulator
@ NIED, Shinjo, Japan

Facilities	Specifications		
	Variables	Limitations	Comments
General Conditions in the Cold Room	Temperature	$-30^\circ \rightarrow +25^\circ$	–
	Other Facilities Available	Microscope, thermal imager, high speed video camera, etc	
Snowfall Machine A 	Snowfall Intensity	$0 - 1[mm/h]$	water equivalent
	Crystal Type	Dendrities	$0.5 \rightarrow 5[mm]$
	Area	$3 \times 5[m]$	–
Snowfall Machine B 	Snowfall Intensity	$0 - 5[mm/h]$	water equivalent
	Crystal Type	Sphere	Diameter $0.025[mm]$
	Area	$3 \times 5[m]$	–

Experimental Setup

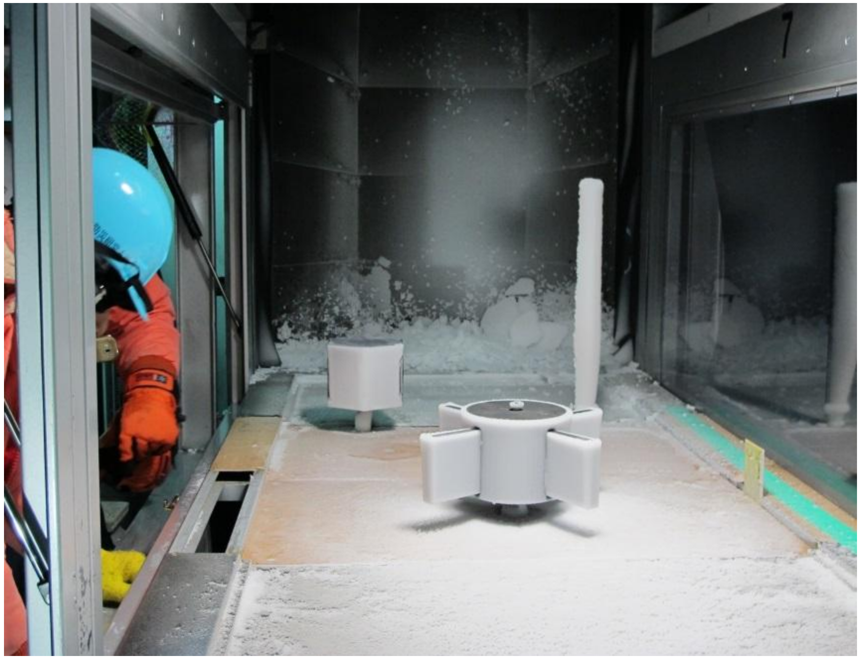




Icing Experimental Conditions

Experimental Setup

Condition/Variables	Specifications
Experimental Facility	CES Icing Wind Tunnel
Sensor	Rotating circle with plates
Ice Type	Rime
Droplet Spectrum	Fine mist ($10 \rightarrow 100[\mu m]$)
Liquid Water Content [1]	$0.5 \rightarrow 0.1[g/m^3]$) (see Fig. 6)
Tunnel Temperature	$-15°$ [C]
Time of Experiment	$110[min]$
Wind Speed	$10[m/s]$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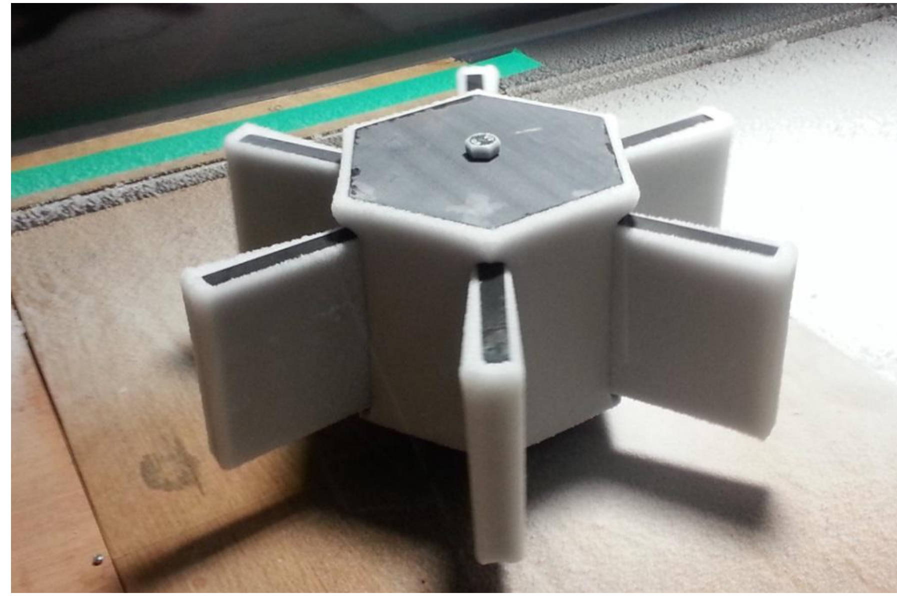
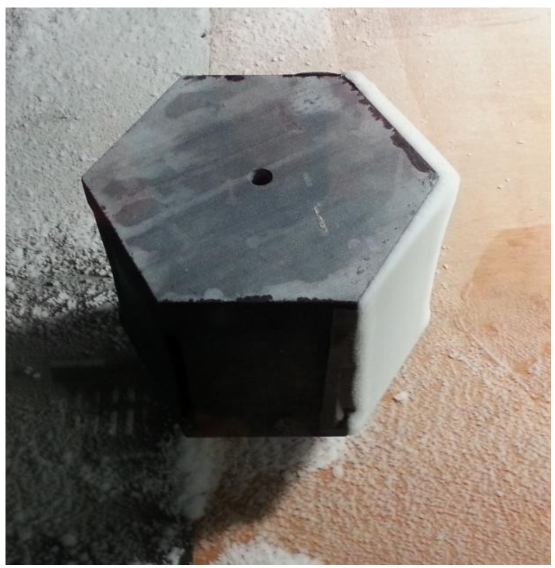
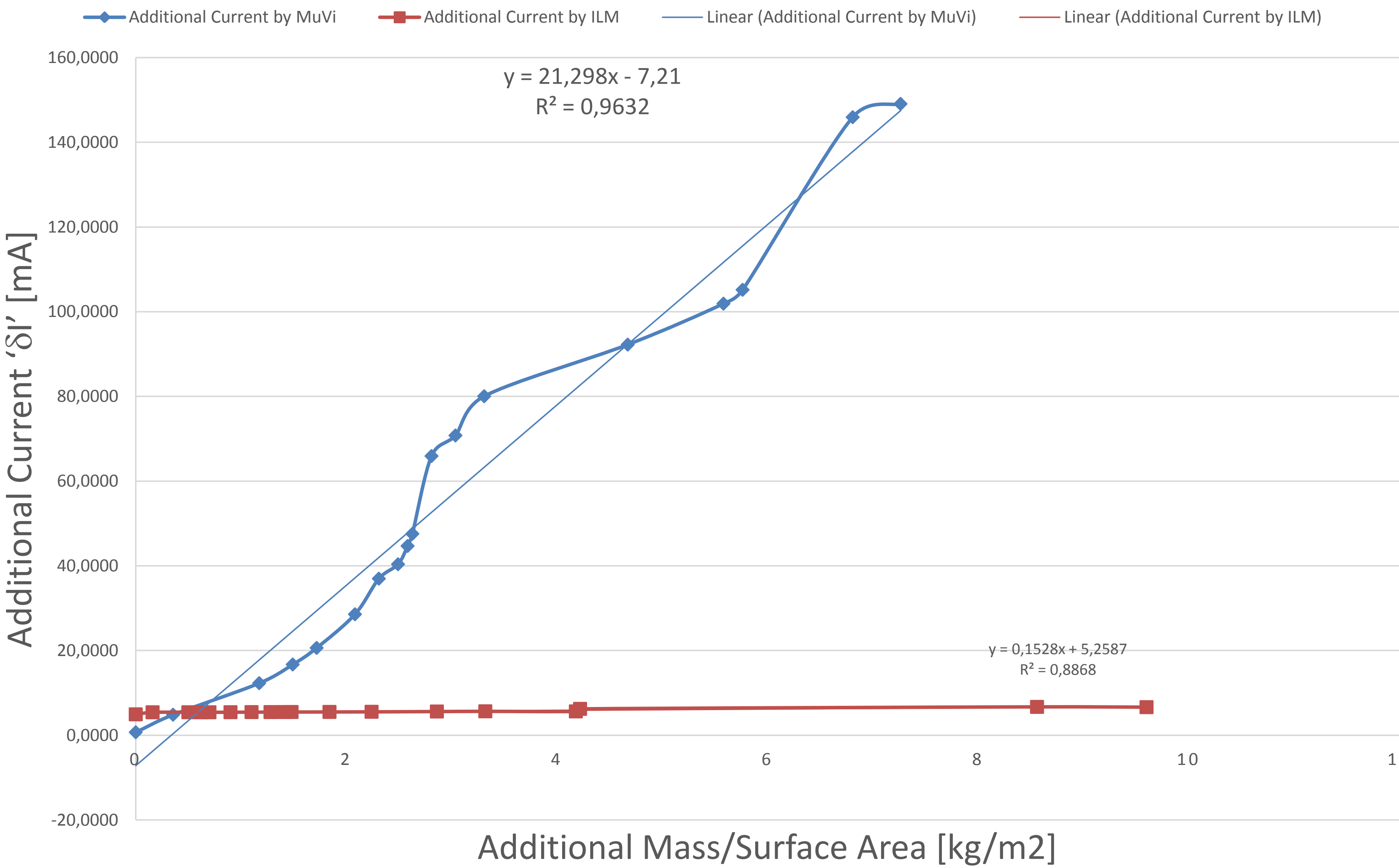
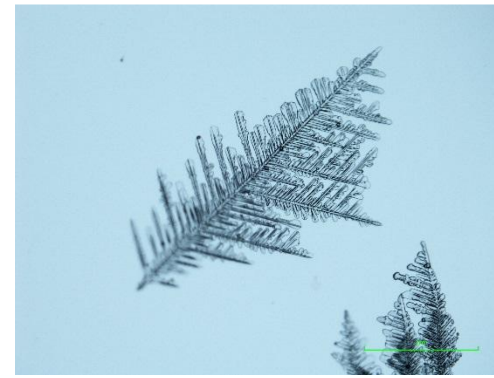



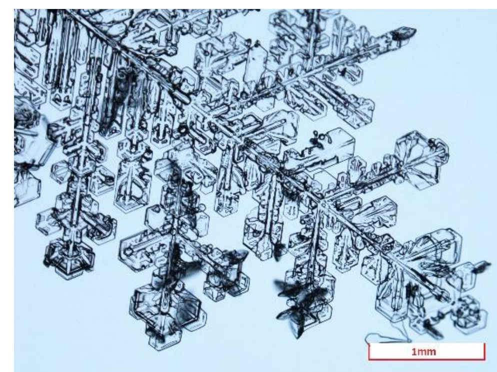

Additional Current – Additional Mass (δI-δm Curve) on MuVi in Icing Conditions



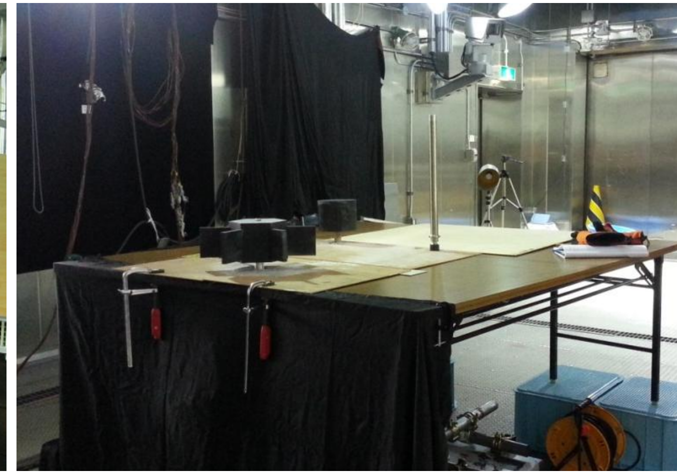
Experimental Conditions in Snow Simulator

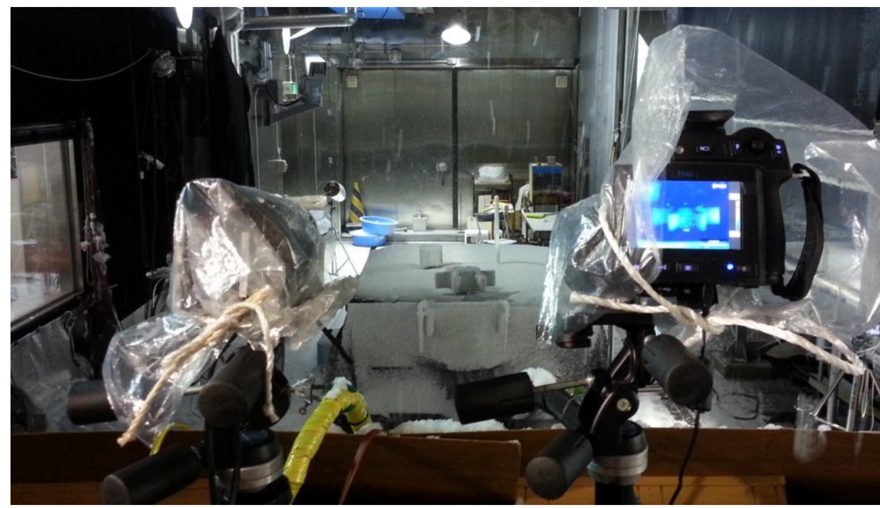
Condition/Variables	Specifications
Snow Type	Snow Type A Dendrities
Crystal Size	$2 \rightarrow 3[mm]$
Sensor 1	Rotating hexagon with plates
Sensor 2	Non rotating cylinder
Sensor 3	Freely rotating IceMonitor
Distance from blower	$277[cm]$
Effective wind speed	$3.5[m/s]$
Cold Room Temperature	$-10°[C]$
Time of Experiment	$210[min]$

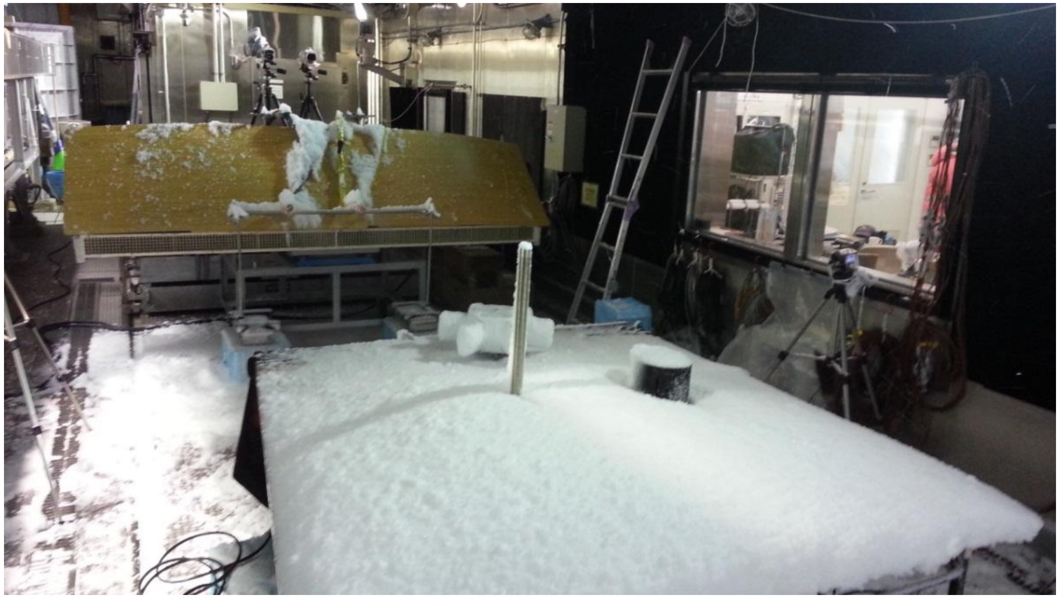


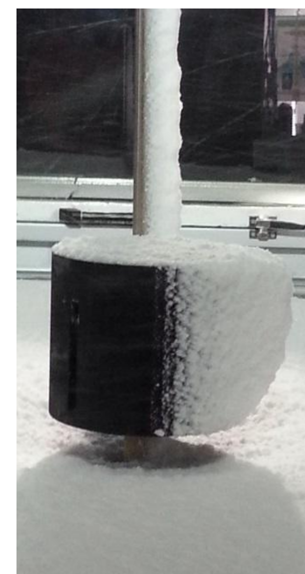


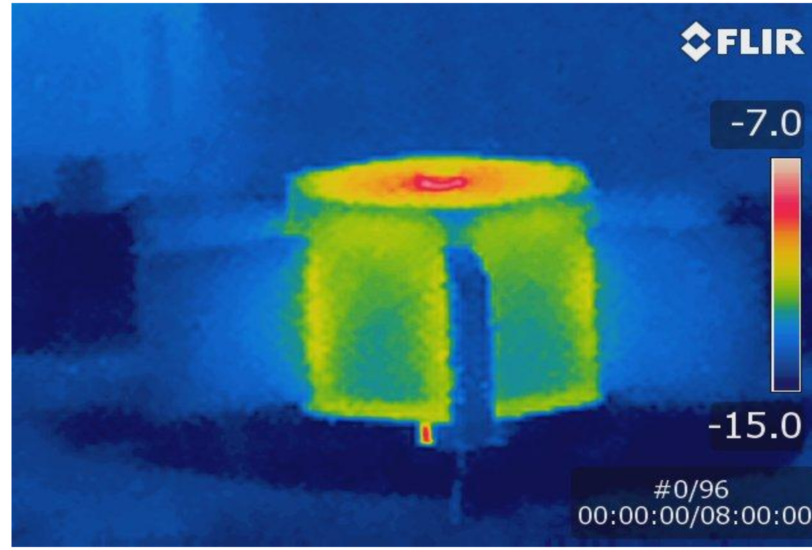
Snow tunnel Experiments







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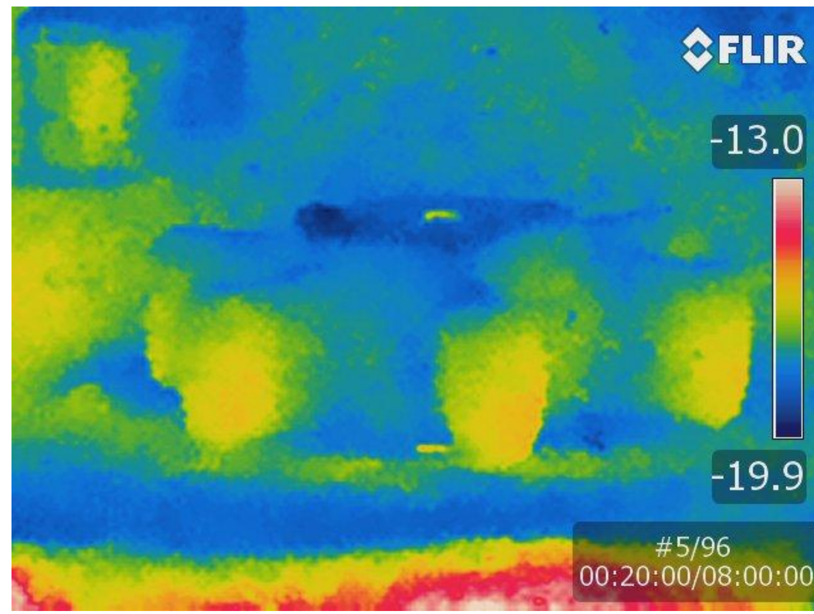
-15.0
#0/96
00:00:00/08:00:00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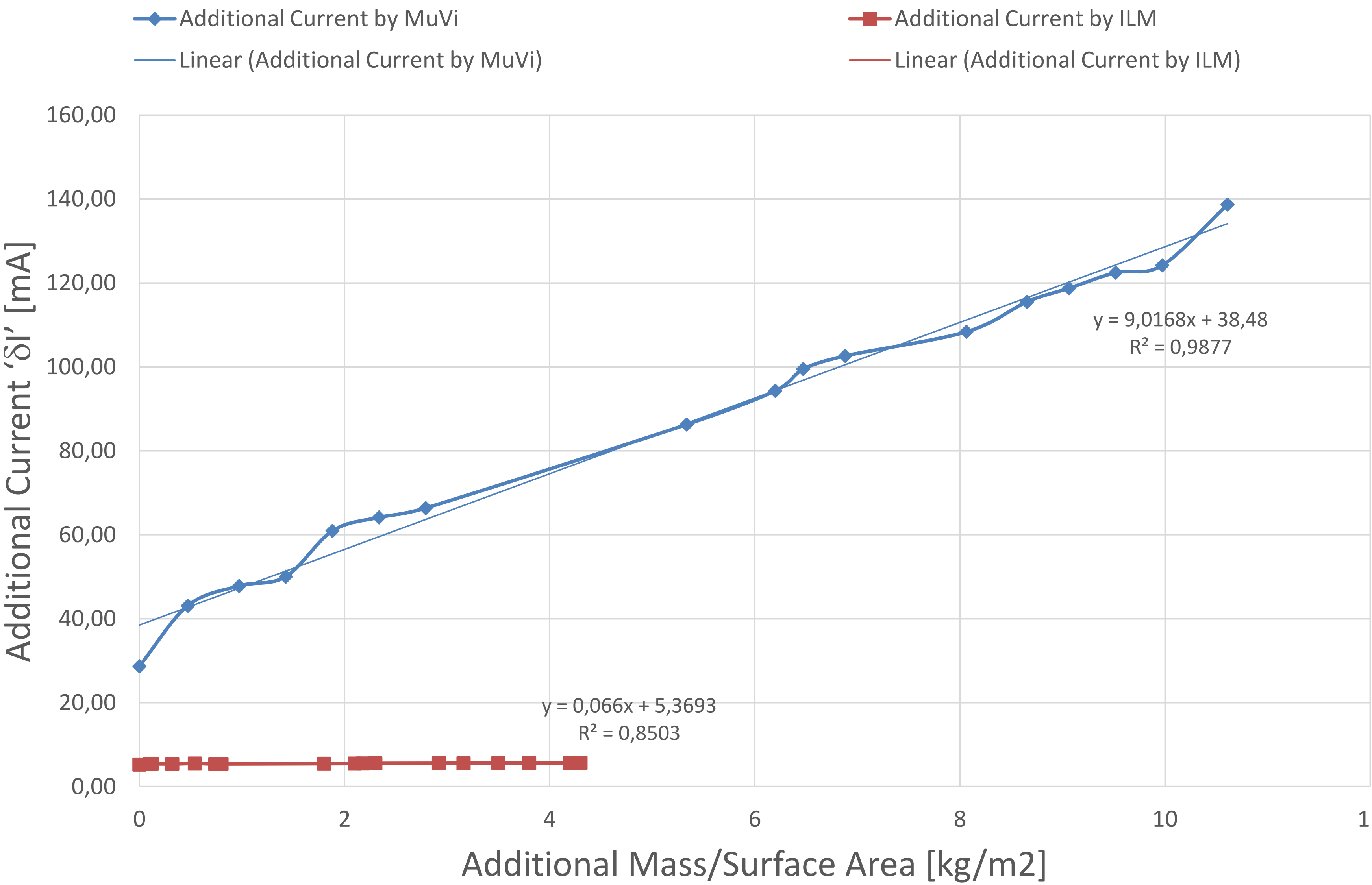
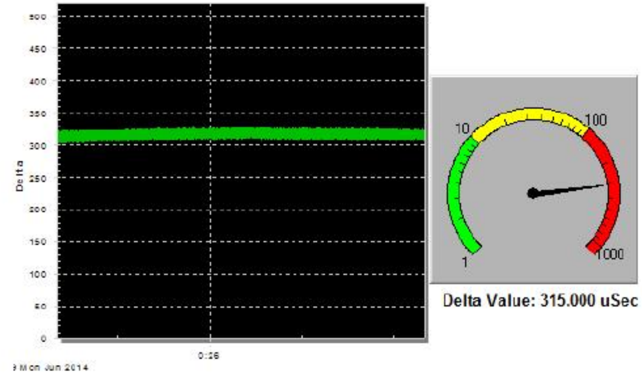
Additional Current – Additional Mass (δI-δm Curve) on MuVi in Snow Conditions



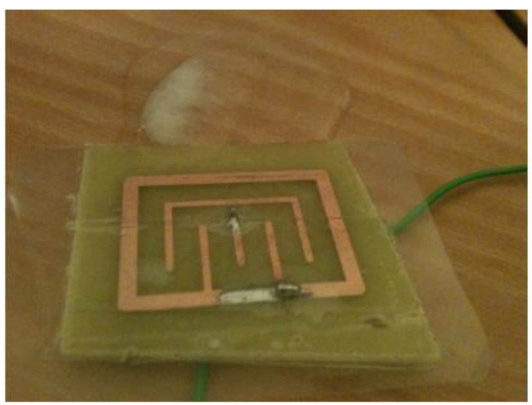
Detecting Icing Event, Type and Melting Rate Using Mutual Charge Transfer Scheme

(a) 5mm pure Ice over electrode

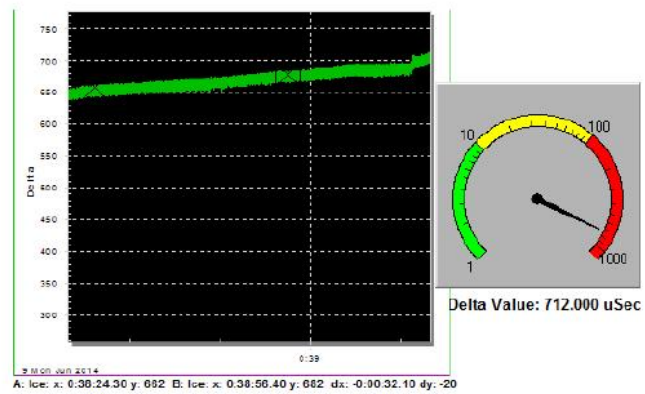


(b) Ice delta value observed

Detecting Ice Using Mutual Charge Transfer Scheme



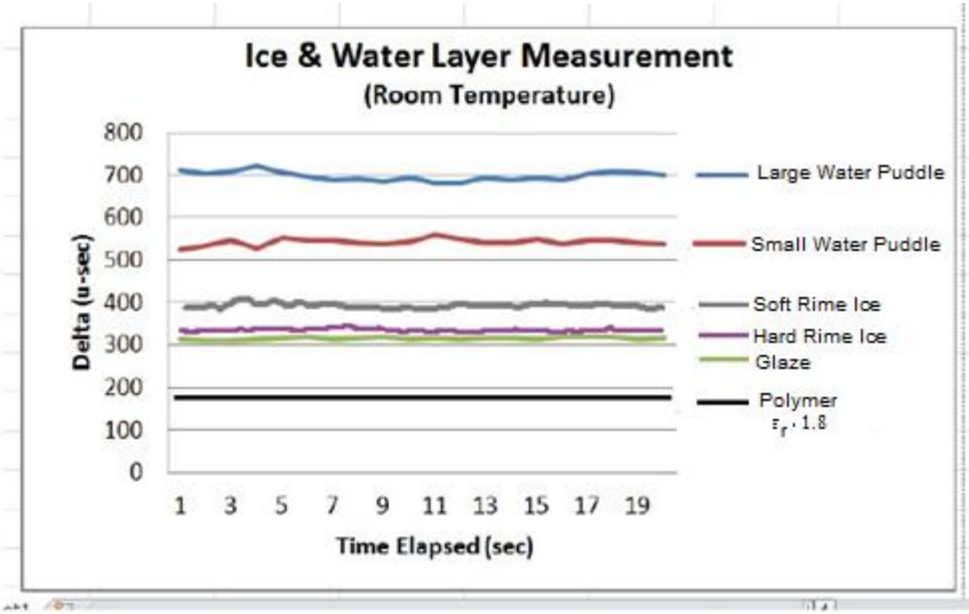
(a) Ice layer removed leaving behind water puddle

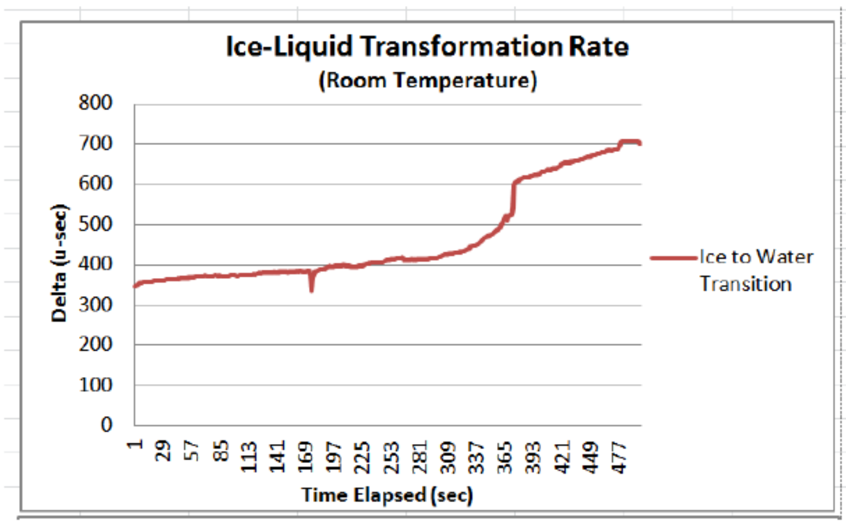


(b) Increase in Delta rate

Detecting Ice Melting Using Mutual Charge Transfer Scheme

Detecting Icing Event, Type and Melting Rate Using Mutual Charge Transfer Scheme





Conclusion

1. Direct measurement techniques of atmospheric ice provides a suitable margin for the development a multipurpose atmospheric icing sensor

2. We have utilized forced roation to measure icing load and icing rate. Also by using forced rotation we were able to see reasonable uniform distribution of ice and snow on the rotary unit.

3. Using Mutual Charge Transfer technique we identified icing type and measured melting rate.

4. For ABS we are interested to test the feasibility of resistive Foils (e.g. CuNi44) for de-icing the sensor.

5. Presently it is a first prototype, hence it have some errors associated with it on which we are working to make it suitable to meet the industrial demands.

I appreciate your attention

I am now open for all questions

ACKNOWLEDGMENT

The work reported in this paper was partially funded by the Research Council of Norway, project no. 195153 and partially by the consortium of the ColdTech project - Sustainable Cold Climate Technology.