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

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Abstract: A new atmospheric icing sensor have been developed by Atmospheric Icing Research Team at Narvik University College which is aimed to deliver ice type using the dielectric variations in the heterogeneous mixture of water, air and pure ice (atmospheric ice). In this study, Debye Model was used to model the permittivity variations and Mughal-Conductivity Relation is used to model the conductivity variations due to frequency and temperature. This paper focusses upon validating the electromagnetic analytical physics of dielectric variation of atmospheric ice with the experimental results using numerical simulations of atmospheric ice deposited uniformly around the rotary atmospheric icing sensor MuVi-Graphene.

Keywords: Atmospheric Ice; Debye Model; UDR; MuVi Graphene;

1. Introduction

1.1 Atmospheric Ice [1]

It primarily occurs due to the accretion of ice on structures or objects under certain conditions. Generally an icing event is defined as periods of time where the temperature is below 0ºC and the relative humidity is above 95%. Ice accretion can be defined as, *any process of ice build up and snow accretion on the surface of objects exposed to the atmosphere*} [2]. Liquid below 0ºC is called supercooled liquid which creates atmospheric icing. This accretion can take place either due to freezing precipitation or freezing fog. It is primarily freezing fog that causes this accumulation which occurs mainly on mountaintops which is particularly dominant in Norway [3]. It depends mainly on the shape of the object, wind speed, temperature, liquid water content (amount of liquid water in a given volume of air) and droplet size distribution (conventionally known as the median volume diameter).

Sometimes ice crystals have a thin coating of water even at temperatures well below freezing which form *clouds*. These ice crystals join together to form flakes and reach ground as snow via air passage with temperature less than zero [4]. *Snow crystal* forms when tiny supercooled cloud droplets (about 10μm in diameter) freeze. However if the outer coating of water freezes of the combined ice crystals during its path via a air passage with temperature less than zero then they form *snow pellets* which are sometimes called as *graupel*. Also if there is a hot layer of air just below the cold layer of air then they reach ground as *sleet*. Sometimes these small droplets with water coating are not successful in combining with other droplets and they get affected by the surrounding air currents but eventually they fall on the surface, they are called *drizzle* which is different then *fog* as it doesn't fall. *Drizzle drops* are of 0.5mm but drops larger than this are *raindrops*. *Hail* is another form of ice. Ice crystals when drop towards the surface they are sometimes passed through very moist air passage due to which they are coated with liquid water which by strong wind is moved upward where water freezes and then then they move down and get covered by liquid water and then moves up to become solid. This process is continued and then it becomes to fall. *Cloud formation* is motivated by a seed or crystalline skeleton on which very tiny, supercooled water droplets can freeze to form *snowflakes* or *soft ice* (*graupel*). Naturally these seeds are random particles of soil, dust, sand, and salt. Artifically they are of two types *glaciogenic* (ice forming e.g. silver iodide or dry ice crystal) or *hygroscopic* (water attracting e.g. small salt particles as potassium chloride).

1.2 Effects/Applications of Atmospheric Icing

Atmospheric icing is a natural phenemenon which cannot be avoided in Cold Regions. However it definitely have some physical loading characteristics on human activities and their associated inventories. On the basis of its loading aspects we can distinguish the effects of atmospheric ice on three classes, which are,

- **Static Loads:** Atmospheric ice, particularly (rime and glaze) is when deposited on some static structure, it increases its mechanical weights. Hence it constrains, the design characteristics (particularly factor of safety) of any civil or mechanical structure to be developed in Cold Regions.

- **Dynamic Loads:** This atmospheric ice, when deposited on the dynamic structures e.g. free dynamic structure as like power cables and motorized dynamic structures as like wind turbines or automobile or ships/boats create additional dynamic loads on these surfaces, which need to overcome by either anti/de icing techniques in case of free dynamic structures or through increasing the power delivered to such systems.

- **Wind Action on iced structure:** It is expected that if the structure is iced, its effective geometry will be altered which in turn reduces the aerodynamic efficiency of structures. This additional drag cannot be completely controlled however efficient anti/de icing techniques through a good feedback from atmospheric icing sensor may reduce the losses.

Atmospheric ice can be a big problem for different industries working in Cold Regions. The potential applications of atmospheric icing sensor for the affected stakeholders can be,

- **Wind Turbine Industry:** One can improve the efficiency of Wind Turbines by installing an atmospheric icing sensory network, which should control turbine pitch by providing feedback to filter out the atmospheric icing loading and rate errors

- **Oil and Gas Industry due their Onshore and Offshore Installations:** These sensors can be utilized in the big installations of oil and gas platforms in Arctic Region. The output from these sensors can be a good feedback for active monitoring of atmospheric icing activities and its remedies through a good anti/de icing system

- **Automobiles Industry:** In Automotive industry these sensor are required to be installed in order to sense the real time atmospheric icing activity on the road surfaces. These sensors can be interconnected with the Road Services via GPS so that accelerated responses for road maintainenece can be conducted.

- **Power Industry due to the ice on the long power networks:** On power networks, one cannot completely calculate the icing load (which can be very critical). This load if it remains on the power line can be less dangerous than if it suddenly falls its reaction can damage the system. However active monitoring of icing rate and icing load may reduce this problem if it is connected with some semi active dampers (e.g. magnetorheological damper) mounted on the power cable connections on the pole.

2. Atmospheric Icing Sensors

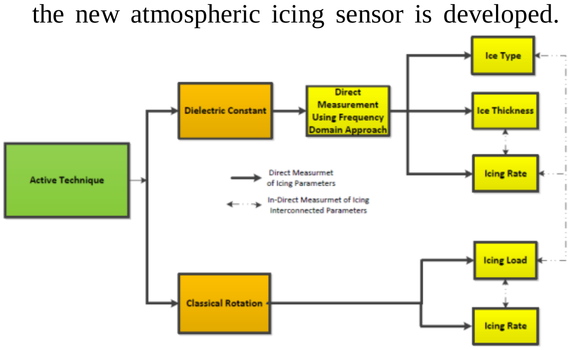
To design a new atmospheric icing sensor, it is important to understand the existing atmospheric ice detection/measurement techniques. It is found that atmospheric icing sensors, which are capable of delivering maximum information are based upon direct measurement of the physical properties (electrical or mechanical) of atmospheric ice. Based upon the study conducted during this this part, it is found that sensors based upon the application of complex relative permittivity variations for different types of atmospheric ice at different ambient conditions offer good potential to detect atmospheric ice type, thickness and rate with minimum loading errors (effects of freezing ambient environment) due to their capacitive nature. This indicates that sensors based on capacitive and impedance measurement techniques are mostly suitable for the development of robust ice measurement sensors with minimum loading errors.

3. Background about Previous Publications in Comsol Multiphysics Conference

In [5] a numerical study was conducted to formulate the Debye equations using the experimental results of [6], [7] which forms a basis for the dielectric based sensing technique for atmospheric icing at different temperature. Modeling wet snow was much more difficult then it was initially understood as it involved three dielectrics water, ice and air. Although some mathematical relations do exist for dry snow but for wet snow even there are not enough mathematical study which can be very interesting to formulate and to justify numerically. Also in [5] conductivity was assumed to be a function of excitation frequency but it was not completely true as it also depended on temperature which was later formulated in [8]. In this publication the preliminary geometry of new atmospheric sensor titled as 'MuVi-Graphene would be discussed.

4. MuVi-Graphene Conceptual Design

In this part focus is upon the analytical modeling of dielectric equations for atmospheric ice which will be a framework of conceptual design. Some new relations of atmospheric ice conductivity and dielectric equations for dry snow are developed. Keeping in view the limitations of available sensors in the market, it is aimed to develop a sensor which should detect ice, icing type, icing rate and icing load; all by one hybrid sensory unit. It is also important to understand that all of the atmospheric icing deposition variables are inter-related with each other as e.g. if the interest is to measure the ice type then it is related with the icing load as both ice and snow have different densities, similarly if we are interested to measure the icing rate using some impedance or capacitive measurement technique then it can be associated with the icing rate using rate of change of icing load. Keeping these design understandings, a flow diagram of the new atmospheric icing sensor is developed.



This can be seen in Flow Chart. 1.

Flow Chart 1. Working Principle of MuVi Graphene

As it can be seen in this flow chart diagram that the icing type, icing rate and ice thickness can be measured by adapting the dielectric variations relationship for atmospheric which would be shortly explained during this paper. On the other hand icing load and icing rate are thought to utilize the rotary physics. This was analytically understood using [9] but it is left to be validated after finalazing the geometry during the experimental phase [1] after selection of all rotary components during the detail design phase.

4.1 Using Multiphysics Solver for estimating Dielectric Properties [10]

The problem of detecting the different types of atmospheric ice using dielectric variations at macroscopic level starts with a understanding of Electromagnetic equations of Maxwell given by Eq. 1 at suitable boundary conditions. In these equations **E**[V/m] is the Electric Field Intensity, **D**[C/m^2] is the electric displacement or electric flux density, **H**[A/m] is the magnetic field intensity, **B**[T] is the magnetic flux density, **J**[A/m^2] is the current density and **ρ**[C/m^3]$ is the electric charge density.

$$\begin{aligned} &\nabla \times H = J + \partial D / \partial t \ \text{ Maxwell Ampere's Law} \\ &\nabla \times E = -\partial B / \partial t \ \text{ Faraday's Law} \\ &\nabla \bullet D = \rho \ \text{ Guass Law(Electric Form)} \\ &\nabla \bullet B = 0 \ \text{ Guass Law(Magnetic Form)} \end{aligned} \tag{1}$$

Also the equation of continuity is mathematically defined as,

$$\nabla \bullet J = -\frac{\partial \rho}{\partial t} \tag{2}$$

From the above Eq. (1) and Eq. (2) an independent system[1] can be formulated. Now as the electric polarization vector **P**[2] can be related

[1] using the Maxwell Ampere's Law, Faraday's Law and Guass Law (electric or magnetic) or Continuity Equation

[2] P is the polarization capability of material under the presence of electric field or the volume density of electric dipole moments. Permanent dipoles have a nonzero **P** also when there is no electric field.

to electric field **E** by the relationship $P=\varepsilon_\circ \chi_e E$ where χ_e (defined in [8]) can be used in the constitutive relation of electric displacement field **D** for the properties of the medium and mathematically described as Eq.(3).

$$D=\varepsilon_0 E+P=\varepsilon_0\left(1+\chi_e\right)E=\varepsilon_0\varepsilon_r E \quad (3)$$

where ε_r is the relative permittivity of dielectric medium. This ε_r will be analytically modeled during in [11]. Electrostatics interface under the AC/DC Physics was used for the simulations as the frequencies to be dealt are low therefore dielectric variations where the time at which the the charge relaxation time is very large compared to the applied excitation changes for the range of frequencies to determine dielectric variations). This leads to the charge distribution is considered as model input which can be solved easily by electric potential **V**. Mathematically under static conditions, the electric potential is defined as,

$$E=-\nabla V \quad (4)$$

where **E** is the vector electric field. Now using the constitutive relation of $D=\varepsilon_\circ E+P$, the Guass Law can be described as a variant of Poisson's Equation, given as,

$$-\nabla \bullet \left(\varepsilon_\circ \nabla V-P\right)=\rho \quad (5)$$

where $\varepsilon_\circ$ [F/m] is the permittivity of vacuum, **P**[C/m^2] is the electric polarization vector, ρ[C/m^3]$ is the space charge density. The Eq. (5) describes the electrostatics field in dielectric materials.

4.2 Mathematical Modeling of Conductivity

As discussed that the atmospheric ice is a heterogeneous materials with different materials, which are conductive (water) and insulating (ice). Jonscher's proposed Universal Dielectric Response UDR [12] is not sufficient for such materials, as it only reflects conductivity as a nonlinear function of frequency, whereas at lower temperatures dipolar vibrations are also very sensitive to temperature. Here a more robust analytical model of conductivity as a function of frequency and temperature is proposed in [13] but is shown implicitly which is numerically solved using Comsol. The results are then compared with the experimentally determined conductivity values of atmospheric ice, see [8]. The proposed conductivity equation is therefore given as Eq. (6),

$$\sigma(\omega,T)=\sigma_s(T)+\left(\sigma_\infty(T)-\sigma_s(T)\right)\left(\frac{\omega}{\omega_p}\right)^{\frac{T-T_{cuttoff\,1}}{T_{cuttoff\,2}-T_{cuttoff\,1}}} \quad (6).$$

5. MuVi Graphene Preliminary Design

After understanding the necessary physics and modeling the analytical dielectric relations supported by lab based experimental results, the basic geometry of the MuVi Graphene is finalized during this part. As it is understood from Sec. (4), that MuVi-Graphene is a rotary atmospheric icing sensor, therefore in this part, using some basic understandings of rotary dynamics a geometry of the sensor are outlined. This geometrical dimensions are not aimed to be fixed at this stage, however some multiphysics simulations are done to probe into the physical potential of this technique by adopting the ε_r equations developed during in [11]. After two months of thorough thought process, a preliminary design of new product was developed with the potential designs of the rotary parts displayed in Fig. (1).

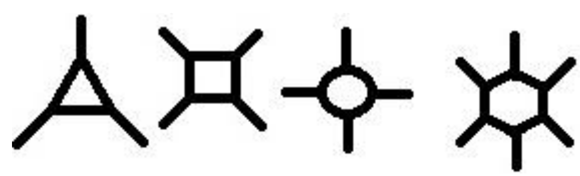


Fig 1. Prospective Physical Designs of MuVi-Graphene [1]

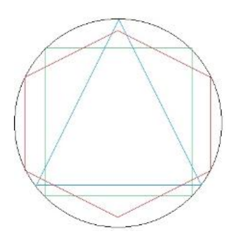
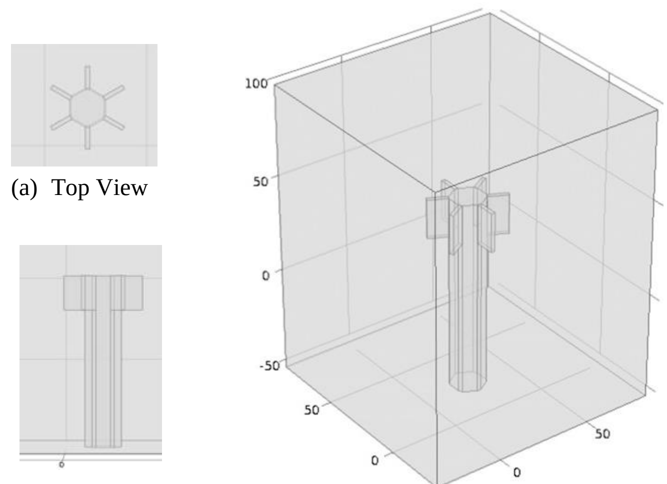


Fig 2. Geometry Selection of MuVi-Graphene of MuVi-Graphene [1]

Through some background understanding of physics, the potential quality of the four designs (Fig. (1)) is mentioned in Tab. (1). Now this prioritizing is based upon theoretical understanding without any analytical or experimental proof, as it was just a conceptual choice for geometry selection, as to carry on the design process. Once this selection had some flaws then there is still enough chance to optimize the design. Considering the constrains that all of these mentioned geometries are inside a circle (see Fig. (3)), it can be seen in Tab. (1) that for the rotational inertia of triangular appear to be most suitable as it has the least rotational mass when they are compared this with hexagon and circle. However if a rank of 2 is graded for a pair of capacitor plates (this constrain is important because the sensory system is rotary therefore robust measurements are needed around the complete sensory unit) then hexagon appeared to be best for this. Similarly if aerodynamic efficiency (as the sensor need to be exposed to vulnerable environmental conditions) of different rotary geometries is considered then triangular cross section appears to be worst due to the additional drag and wake around the sensor (an assumption), however in this case circle appears to be the best. This is a rotary sensor therefore it has to stable, however at this stage detailed mathematical understanding was not required but as an overall circle and hexagon are thought to be more stable due to the less sharp edges (only obtuse angles between circle and hexagon whereas circle had a right angles and triangle has acute angles which may deteriorate their stability due to ice gusts). If mounting of capacitor plates is graded then it is lowest in triangular and maximum in hexagon along with suitable space to mount these plates which is even not found in circle hence hexagon appeared to more robust and redundant then circle and all other geometries. As an overall assessment it can seen that hexagon design appeared to be most suitable with a top grading of 27 but it was just an initial prioritization from the available selections. After shortlisting hexagon and as a designer of this new hybrid (multi-purpose) atmospheric icing sensor, this sensor is titled as MuVi-Graphene. This lead to start a more detailed multiphysics simulation on this sensor using Comsol as a solver.

Table 1. Prioritizing the Preliminary Design of MuVi-Graphene
where 1=Poor, 2=Fair, 3=Good, 4=Very Good, 5=Excellent

Potentials Features	**Prospective Designs**			
	Traingular	*Square*	*Circular*	*Hexagon*
Rotational Inertia	5	4	4	3
Capacitive Plate Pair	2	4	4	5
Aerodynamic Efficiency	2	3	5	4
Stability due to wind load and icing loads	2	4	5	5
Redundancy	2	4	4	5
Robustness	2	4	4	5
SUM	***15***	***23***	***26***	***27***



(a) Top View
(b).Front/Side View
(c).Axiometric View

Fig 3. Preliminary Design of MuVi-Graphene [1]

5.1 Modeling Initial Geometry in Comsol

Using Multiphysics analysis tool Comsol, a simple 3D geometry of MuVi Graphene was developed as can be seen in Fig. (3). In this figure, the rotary part is a hexagon with six capacitive plates such that all adjacent plates are at opposite potential. This is a rotary sensor therefore we have assumed a uniform ice distribution around the sensor. The dimensions of the sensor can be seen in Fig. 4 where a free triangular mesh was used with 664914 elements. No mesh sensitivity analysis was done as it was not required. However the boundary conditions were such that three plates were at zero potential and three were at 10 Volts. The results can of this analysis can be seen from Fig. 5 till Fig. 11 and these results are discussed in Sec. 6.

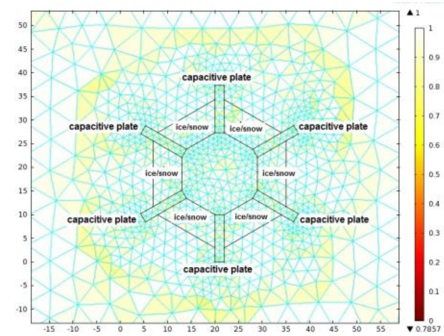


Fig 4. 2D Mesh of MuVi-Graphene

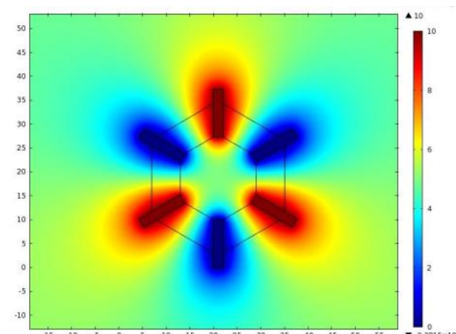


Fig 5. Voltage Distribution MuVi Graphene

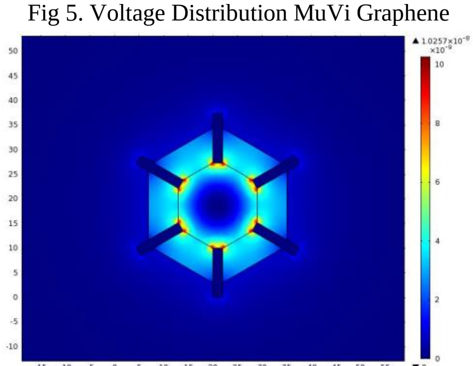


Fig 6. Displacment Field Norm for Pure Ice

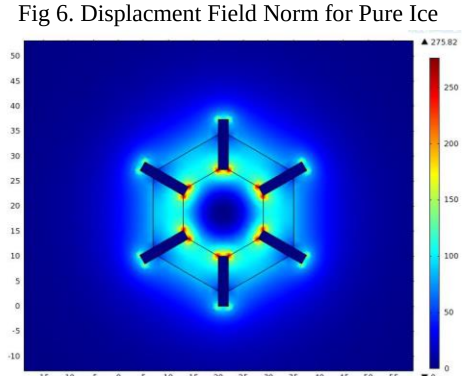


Fig 7. Electric Field Norm for Pure Ice

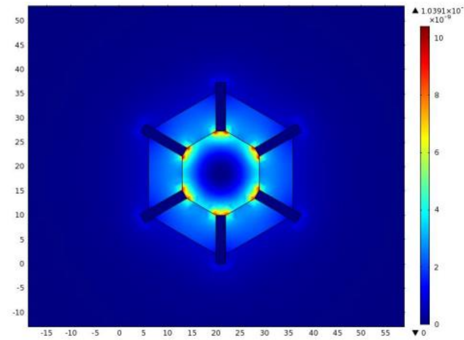


Fig 8. Displacment Field Norm for Dry Snow (ρ=0.8[3])

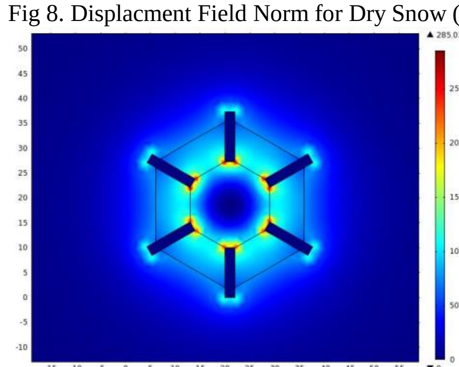


Fig 9. Electric Field Norm for Dry Snow (ρ=0.8)

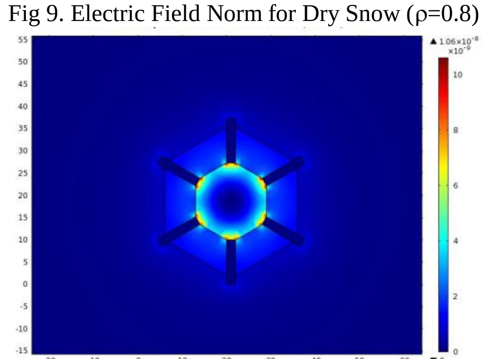


Fig 10. Displacment Field Norm - Dry Snow (ρ=0.4)

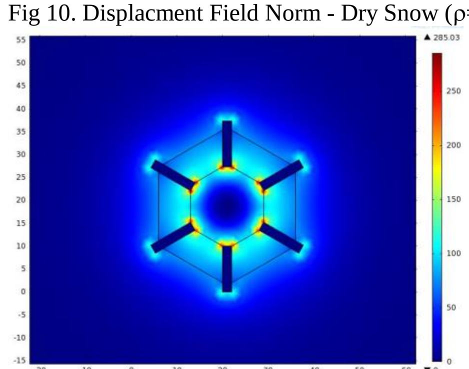


Fig 11. Electric Field Norm - Dry Snow (ρ=0.4)

[3] For details about ρ see [10]

5.2 Results and Discussions

As the proposed physical sensor have six capacitive plates which are coupled with each other such that if one plate is at 0 potential then its neighbor is at some positive potential which in our case is 9[V]. As it can be seen in Fig. (6) that the surface displacement field show very dominant deviation such that, the areas where atmospheric ice is deposited. For a comparative chart see Tab. 2. Now it can be observed from Fig. (7) that for pure Ice the electric field intensity is 147.7[V/m] and displacement field is around $5.49x10^{-9}$[C/m^2]. Similarly if atmospheric ice (dry ice) with $\rho = 0.8$ (see [11]} is considered then distinguishing values of electric field intensity as 152.63[V/m], (see Fig. (8)) and displacement field of $3.88x10^{-9}$[C/m^2], (see Fig. (9)). Likewise if $\rho = 0.4$ then a deviation in values of electric field intensity as 152.63[V/m], (see Fig. 10) and displacement field of $3.88x10^{-9}$[C/m^2], (see Fig. 11) can be found. These results show that the variation in ε_r and conductivity σ plays a very dominant role in detecting different atmospheric ice types. Parametric simulation was done using Multiphysics solver Comsol (see Fig. 12 and 13) to allow non-uniform ice deposition on the capacitive plates as it was yet not sure that how atmospheric ice would be deposited when the sensor would be rotated at constant rpm. Therefore one plate in the rotation directions was covered 90% with ice whereas the adjacent plate in hiding from the rotation side was covered 10% with ice. The results of Fig. 12 and 13 still indicate that indicate that we can still detect the type of atmospheric ice, if actual sensor is properly calibrated.

Tab 2. Multiphysics results to distinguish atmospheric ice

Atmospheric Ice	Multiphysics Variables	
	Electric Field Norm	**Displacment Field Norm**
Pure Ice	147.7	$5.49x10^{-9}$
Dry Snow, $\rho = 0.8$	152.63	$3.88x10^{-9}$
Dry Snow, $\rho = 0.4$	156.6	$2.76x10^{-9}$

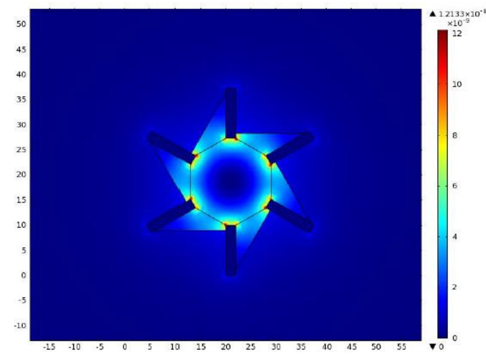


Fig 12. Displacement Field Norm during non uniform pure ice deposition

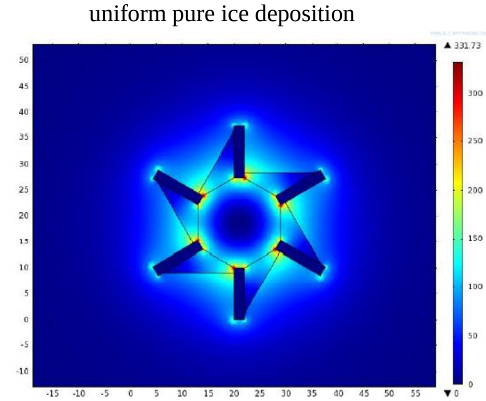


Fig 13.Electric Field during non uniform pure ice deposition

6. Conclusions

Multiphysics simulation using Comsol laid the foundation of MuVi Graphene (Product Design). This bridged the gap to understand the working principle of the sensor and its associated capacitive physics (primarily). The numerical results of from Comsol were later on compared with the experimental results mentioned in [14], [15] and [16]. Similary the basis of Mughal Conductivity Equation for atmospheric ice was also laid down using the Multiphysics solver. It was later on recognized that putting capacitive plates with opposite polarity might not be a good solution as their would be lot of chances of short circuiting during an icing event with relative humidity of more than 80%. Therefore after careful understanding of mutual charge transfer technique, it is presently the utilized physics for detecting atmospheric ice, icing type and icing rate, for details see [17].

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