Using Mutual Charge Scheme to Measure Salinity of Ice

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***Abstract*—For offshore measurements in Cold Regions, salinity of ice is also a critical parameter (together with many other parameters such as icing type, load, icing rate and melting rate) to be identified in order to optimize the performance of anti/de icing systems. Although there are some available sensory solutions in the market to measure real time salinity levels of water, however there are still not many real time techniques or solutions to measure the salinity of ice. In this research task, mutual charge transfer technique is utilized to measure the zero crossover values of different samples of ice and water with varying salt ratios. The aim of this paper is therefore to discuss the testing methodology and testing results.**

Keywords–Atmospheric Icing Sensor; Offshore; Salinity; Zero Cross Over; Mutual Charge Transfer.

I. INTRODUCTION

For safer operations in High North, firstly it is important to understand the difficulties that may lead to people and inventory hazards. Continues melting of ice in high north is leading to accelerate the research and development activities towards this part of the world [1]. In order to plan for technological advancements in Cold Regions, it is critical to carefully understand the ice accretion characteristics on vulnerable structures and inventory. Icing on offshore structures have not yet been considered as major hindrance by maritime industry, however it may not be justified in near future. Feedback about icing parameters such as icing rate, type and icing load are considered to be very important for an Intelligent Anti/De Icing system. However, if such a system is utilized during an Offshore Application then real time salinity measurements are also considered to be critically associated with the ice accretion on structures. This leads to define atmospheric icing and sea spray icing. *Atmospheric Icing* is formed during the supercooled transition of water, it freezes as soon as it comes into contact with a cooled surface at temperature far below the freezing point. This ice accretion produces a hard layer of ice on all surfaces and is responsible for different challenges for safe operations specially related with communication, navigation and logistics. Nevertheless, if the offshore vessel is small than this accretion also effects its stability. Also if the sea spray icing also occurs at the same time then it amplifies the risk the accident. *Sea Spray Icing* is in fact more critical risk than the atmospheric icing. As the name suggests, this icing is more saline in nature (freezing point of salt water is $-1.7^{\circ} \rightarrow -1.9^{\circ}C$ till $-30^{\circ}C$ and critically depend upon salinity levels). It may be initiated when the portion of vessel meets the ocean waves or the blowing wind brings transports the water from ocean crests. It is however more dependent on the relative speed of the vessel and the wind (typically it starts at $8m/s$) and typically limited to $15 \rightarrow 20m$ above sea level. The advantage of this icing is that it supports the melting and cleaning of ice formed on the deck. However, if the scuppers freeze or the railing are covered with ice, then this water is trapped and frozen [2]. It is a general observation that in arctic seas, icing activity continues throughout the year and the ocean's density is effected more by salinity than by temperature. However, during first two quarters (January till June) atmospheric icing is common whereas during the third quarter (July till October) sea spray icing leads the activity by 50% leaving behind 45% for mixed icing and 9% for atmospheric icing. Generally, during an offshore operation atmospheric icing is not very critical as there it generally occurs on higher parts of ships, which typically get covered with $1 \rightarrow 2cm$ (typically surrounding air temperature is $0^{\circ} \rightarrow -20^{\circ}C$ and wind speed is less than $10m/s$) of thick ice. However, during sea spray icing and mixed icing, ice thickness reaches $1m$ in some cases. Table I reflects some icing intensities and prevailing surrounding parameters [2].

TABLE I. TYPICAL ICING INTENSITIES DURING OFFSHORE ACTIVITY [2]

Intensity Category	Icing Intensity		Temperature	Wind Speed
	ton/hr	cm/hr	$^{\circ}C$	m/s
Slow	< 1.5	< 1	$0 \rightarrow 3$	Any Speed
			≤ -3	< 7
Fast	$1.5 \rightarrow 4$	$1 \rightarrow 3$	$-3^{\circ} \rightarrow -8$	$7 \rightarrow 15$
Very Fast	> 4	> 3	≤ -8	> 15

This paper is divided into five sections. As already discussed, Section I is an introduction to form the basis to measure salinity as an important parameter for real time offshore measurements. In the next section II, it is aimed to describe the present salinity measurement techniques, which are presently limited to remote sensing only. Section III will be an overview of mutual charge transfer scheme and in section IV hardware, experimental setup and results will be discussed. In section V, the results will be discussed followed by the conclusions and future work.

II. PRESENT SALINITY MEASUREMENT TECHNIQUES

The present real time salinity measurement techniques are restricted to measure the salinity of water. Salinometer (and Total Dissolved Solids 'TDS' meter) is a conventional instrument, which is designed to measure the salinity of dissolved salt content in a solution.

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Technically salinity increases the conductivity of a solution, therefore the measuring sensor normally have electrical conductivity meter calibrated according to the salinity levels. Salinity also changes the specific gravity of the solution therefore it is also measured through hydrometer sometimes. However, in marine aquarium, sometimes a refractometer is used to measure the salinity and specific gravity of the water.

Presently the sea surface salinity variations are detected using remote sensing techniques such as using passive microwave technology (typically in the range of $1-3GHz$L & S bands). The clouds are transparent to such radiation, however sea ice emit such radiation at relatively low energy levels, which are difficult to measure over a smaller area [3][4]. Since 2002, NASA uses Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E) sensor installed on Aqua Satellite for measuring the time series of sea ice data to complement the available sea ice data from 1972 [4]. The first global salinity map of Earth's Ocean Surface is revealed by NASA's Aquarius Instrument by recording the data from August 25 till September 2011, see Fig. 1.

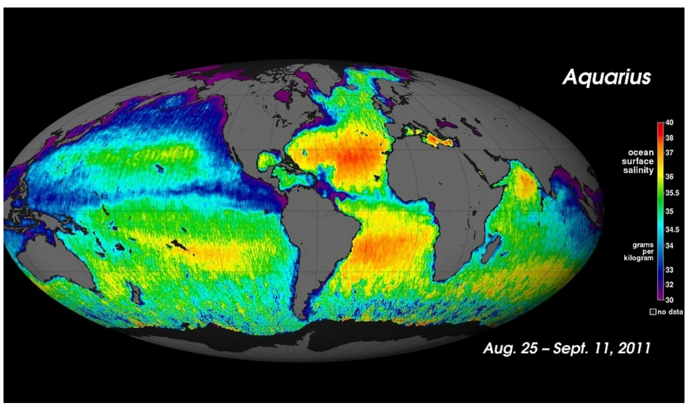

Figure 1. Salt of the Earth by Aquarius, NASA [5]

A review of available atmospheric ice sensing techniques is available in [9] followed by the electromagnetism techniques to detect atmospheric ice [11]. A detailed mathematical description to detect atmospheric icing using dielectric based sensing technique, in particular using standard Debye relation [12](see (1)) and its extended versions is available in [10].

$$\varepsilon = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + i\omega\tau_o} - \frac{i\sigma}{\varepsilon_o \omega} \tag{1}$$

where ε is the complex frequency dependent dielectric permittivity; ε_s is the static dielectric permittivity of material; ε_∞ is the high frequency complex dielectric permittivity of the material; $\varepsilon_\circ$ is the dielectric permittivity of the free space; ω is the angular frequency of the signal; $\tau_\circ$ is the relaxation time of the material and σ is the conductivity of the material.

Similarly using the real part of the Debye dielectric permittivity relation [12](see (1)) at $50MHz$ a relation to derive the brine volume fraction and bulk salinity in the first year sea have been developed by Backstrom and Eicken [6]. In [6], three different experiments were conducted using the commercially available capacitive probes such as Stevens Water Monitoring Systems Hydraprobe [7][8] in order to find the possibility to measure both the absolute values of the bulk salinity and changes in bulk salinity. They found good results with large temporal and spacial resolutions, within a reasonable error limit particularly during initial freezing and during ice melt. However, presently there is no available sensor, which can distinguish between different samples of accreted ice with varying salinity levels and deliver the results in a real time.

III. MUTUAL CHARGE TRANSFER

To sense capacitance changes of one order is not difficult; similarly capacitance changes of 10% is although difficult but still not trivial. However, if the capacitance changes are within 1%, in the presence of environmental changes then the measurements can be quite challenging [13]. The charge transfer technique to measure ice carry unique advantage of design flexibility in terms of implementation. The commonly used proximity and capacitive MEMS devices are capable to the influence of dielectric presence. The implementation of this technique has matured over the years and presently they are widely used in industrial automation, human sensory gadgetries (human finger capacitance is around $100pF$) and automobiles even in freezing domains without much variations. The water rejection techniques (water capacitance approximately $50pF$ but largely depends upon dimensions of the sensor) are incorporated in most of these devices. Recently ice detection and melting rate measurement results have been reported in [15] followed by some basic experimentation results [16], it is found that this technique have enough potential to detect and measure atmospheric icing parameters by lowering the voltage sensitivity thresholds (see [17]).

The self or mutual capacitance basics can be employed in the design based on charge transfer method. A small printed circuit board aided with the specific electrode configuration can be manufactured as a basic prototyping icing sensor. The benefit of reshaping the electrodes and design to any form with capability to change different dielectric material suitable to harsh environment can be used as a starting point to develop a prototype. This would enable to detect and measure the icing parameters in real time embedded platform with low power consumption, which is ideal for remote installations. The presented design is principally based on the mutual charge transfer (QMatrix) based icing detection, which is advised by Atmel to work better in high humidity or damp environments where the frequency of water droplets and moisture to be collected on the sensor is higher [18]. Furthermore the preference to mutual charge transfer was based due to the following constrains,

a) Sensitivity: The self capacitance design are more sensitive in nature. As the electric field is spread outwards through the electrode, in the presence of dielectric, ground loading is provided by the external influencing of the object, in our case will be ice or a water film. But with increase in sensitivity comes the inclusion of the noise in the circuitry, which is un-desirable. The noise in self capacitance might be increased so sensitivity tuning is the vital for design based on this methodology. The other factors, which can effect sensitivity are,

- Electrode dimensions and shape
- Ground loading
- Return path
- Supply voltage
- Charging pulses duration

b) RF interference rejection: The mutual capacitance have pairs of electrodes that are always connected to a low impedance circuit, and due to the fact that their electric fields are compact and self-shielded. The pair of electrodes do not respond well to external interference in the environment. In addition, the patent MEMS device $QT60240$ used for the experimentation are spread-spectrum technology based, that is highly efficient for suppressing both radiated emissions and external fields susceptibility. Control panels made with this technology routinely pass susceptibility tests exceeding field strengths of $20V/m$.

c) Dimensional Benefit: Also mutual capacitance through charge transfer principle is preferable when key area for detection is to be defined. To isolate the areas of detection within a specific limit, this works in efficient manner as compared to the self capacitance. With mutual principle, the PCB tracks for detection circuitry can contain longer routing tracks, which could be the important consideration in the prototype embedded design.

d) Moisture suppression: The mutual approach provides two moisture suppression characteristics not present in any other capacitive methodology. First, the presence of a localized water film (due to condensation, mist, or tiny droplets) will induce only a small increase in signal coupling. The contributions to signal coupling caused by moisture will have an influence into the measurement but in the wrong direction of signal of normal readings and hence will cater the false detections. Secondly, the presence of moisture layer, which can conduct charge away are also minimized by the use of narrow *gate timings*. This results in limiting the charge accumulated to a narrow time slot window immediately after the charging pulse edge. As water film can be modeled as a distributed RC network with a time-dependent characteristic, the benefit of narrow gate times (microsecond or less) will greatly suppress the effects of a water films signal potential reduction, further reducing the chances of a false detection. However, this utility of the patented charge transfer based on mutual capacitance have to be modified in ice detection prototype hardware. Hence, the capability of the prototype hardware to distinguish between the thin water film and ice have to be included through PCB design circuity and charge transfer pulses adjustment.

e) Other benefits:

- Temperature stability
- Low power modes

During this research work, experimentation were performed to analyze the measurable response of the icing and liquid ranges with variable salinity levels along with the state transition rates. The initial design was aimed to distinguish the saline ice and saline water layer formation. Later on the design incorporated the saline ice level measurements. The design is kept in the consideration of harsh climatic performance and remote installation mechanism flexible enough to be mounted on various Onshore and Offshore platforms or other sensors as like MuVi-Graphene, see [19]. The necessary condition for a robust flat plate capacitive sensor was to have uniform and sufficient ice deposition on its surface; this has been experimentally demonstrated by Mughal & Virk [20].

IV. Experimental Details

A. Hardware Setup

The hardware implementation of the computing hardware and electrode for icing measurement is shown in Fig. 2. The embedded algorithm of computing hardware was performed using Atmel Studio 6 on the AVR series 8-bit microcontroller with associated peripherals. The in circuit programming was assisted using Atmel STK 500 development kit. The patented charge transfer process is executed by the $QT60240$ device and several charge/discharge cycles are executed based on burst of pulses ranging from $500\mu s \rightarrow 2ms$. The micro-controller initializes the communication through I^2C protocol and determines the change in the zero crossing of detected slope for each charging pulse. Generally, the negative DC voltage ramp for the signal is around $-250mV$, which is achieved by the synchronous switching of capacitors and slope drive cause the zero crossing. The $\tau_{zerocrossover}$ value (differential time measured) is acquired by the μcontroller and stored in a buffer array at the same time. The buffered $\tau_{Zero\,Crossover}$ value is converted to $RS232$ protocol and sent at the baud rate of $19200bits/s$. The resulting data was displayed in a DAQ factory (data acquisition development software) based user interface for further analysis and experimentation for optimizing sensor configuration.

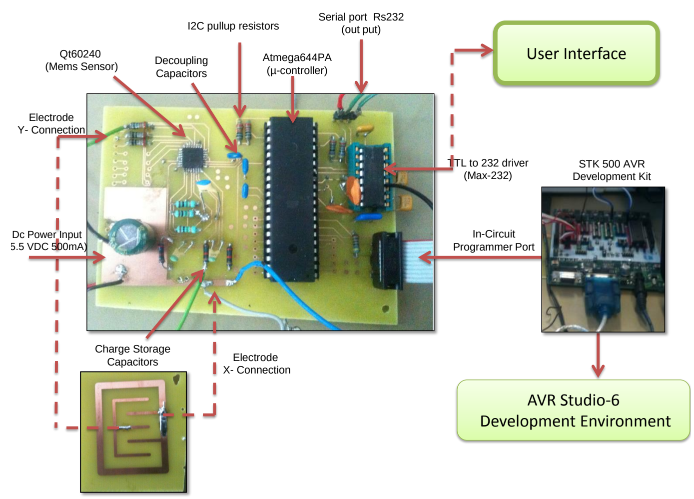

Figure 2. Computing Hardware Module

B. Experimental Setup

A preliminary series of experimentation were performed in Cold Room Chamber of Narvik University College. There are three Cold Rooms where a controlled temperature from $+20 \rightarrow -30°C$ can be maintained. A sample of $100ml$ of water was used as a standard liquid content. Different levels of salt $0 \rightarrow 30g$ were mixed in this water sample and tested by pouring these samples on the electrode plate. Similarly the same salt levels were mixed in different water samples of $100ml$ each and allowed to freeze in the local freezer. The electrode panel was made as a non planar structure where the electrodes and rest of the pcb circuitry are lying on different panels (see Fig. 2). This scheme was preferred over the planar structure (Electrodes and computing hardware on same PCB) keeping in consideration of the cold climate environment. The intention was to make a separate robust electrode panel

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exposed outside the environment to detect and measure the ice whereas the computing hardware is made on a separate PCB house inside protected covering. The overall dimension of electrodes pair used was $26 \times 36mm$ and the other dimensions are:

- X electrode outer border thickness $2.54mm$
- X electrode finger thickness $1.25mm$
- X-Y inter spacing width $3.8mm$
- Y electrode key thickness $1.25mm$

Common front panel dielectric materials include glass, plexiglass and polycarbonate. However, during this experiment all season packaging tape 60041 was used. This tape was used as it has excellent holding power during extreme hot or cold temperatures and made of pressure-sensitive poly material. The $\tau_{ZeroCrossover}$ of the electrode plate with only front panel dielectric tape 60041 was $438\mu s$.

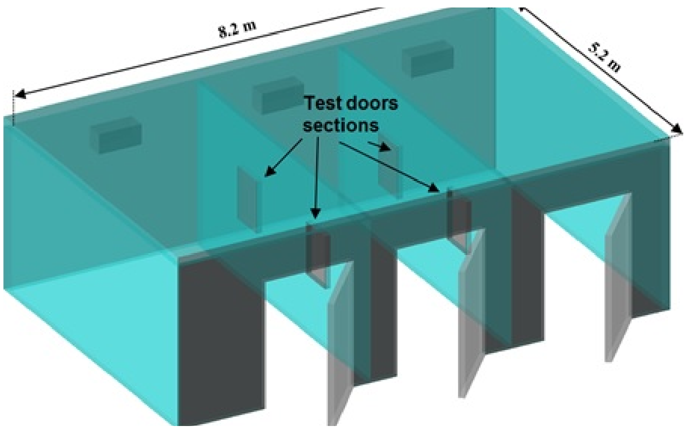

Figure 3. Cold Room Chamber, Narvik University College

C. Results and Discussions

The charge transfer technique outputs $\tau_{Zero\,Crossover}$ as a measurement signal. The results of the experiment are tabulated in Table II and plotted in Fig. 4. The results indicate that as the percentage salinity ratio $\%SR_{ice}$ of ice is varying from $0 \rightarrow 23\%$ the $\tau_{Zero\,Crossover}$ signal varies from $600 \rightarrow 1250\mu s$. Hence, a linear relationship can be found between $\%SR_{ice}$ and $\tau_{Zero\,Crossover}$ with an effective slope of $28\mu s$ (see (2)). However, when the $\%SR_{water}$ of water is plotted against $\tau_{Zero\,Crossover}$ signal, then the slope is not effective to demonstrate the linear variation, however this result do indicate the difference between fresh and saline water (see (3)). The Intercept of this curve is intentionally fixed at $2100\mu s$ in order to indicate the linear relationship between the changing salinity levels in water. One of the possible reason of mutual transfer scheme to not indicate the $\%SR_{water}$ can be associated with the water slippage leaving behind small puddles of water on the electrode plate.

$$\%SR_{ice} = 28\tau_{zero\,crossover} + 559 \tag{2}$$

$$\%SR_{water} = 1.38\tau_{zero\,crossover} + 2100 \tag{3}$$

TABLE II. SALINE WATER AND ICE TESTING RESULTS

Saline Water			
Volume of Waterml	Mass of Salt g	Salt Water Ratio %	Zero Cross Over μs
100	0	0	600
100	5	4.47	700
100	10	9.11	750
100	20	16.7	1000
100	30	23.1	1250
Saline Ice			
Mass of Ice g	Mass of Salt g	Salt Ice Ratio %	Zero CrossOver Value μs
99.7	0	0	1823
99.7	5	4.47	2089
99.7	10	9.11	2120
99.7	20	16.7	2117
99.7	30	23.1	2137

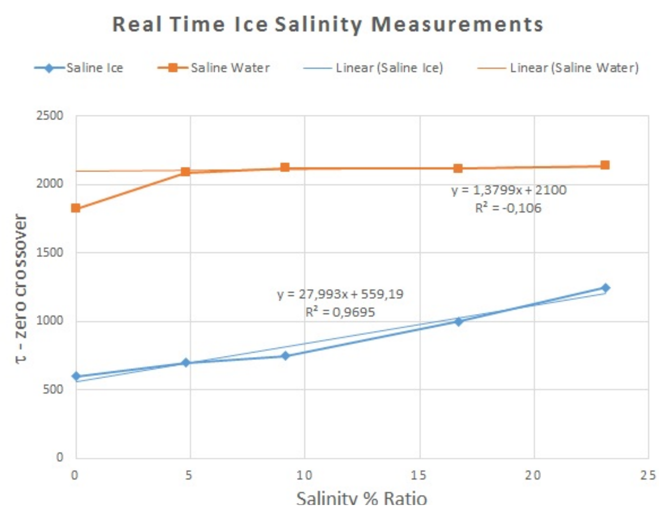

Figure 4. Real Time Ice Salinity Measurements

During the experimentation at room temperature the melting of ice layer/block occurred as a natural process, which could be the case in real environment. This phenomena could also be observed from the $\tau_{zerocrossover}$ measurement as it varies with the melting of ice layer upon the electrode till it slides over the electrode leaving behind the water puddle over the electrode.

D. Limitation

The measurements taken are independently experimented based on the charge transfer technique. The ice samples used were frozen using commercially available freezers.

V. CONCLUSIONS

The icing detection and salinity measurements in harsh cold climate is a demanding challenge. Particularly during an offshore activity, the need is more demanding with the latest developments in the technology and resources. If the parameters such as ice accretion and salinity are measured in real time, then expected damages can be reduced by using them as feedback variables in an intelligent anti/de icing system. The charge transfer technique outputs $\tau_{Zero\,Crossover}$ as a measurement signal. This is a real time output to indicate

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percentage salinity ratio of ice hence there are minimum delays associated with this technique. This is already proven technology therefore the implementation of this technique have matured even in freezing domains without much variations. The results of this experiment indicate that it is possible to use this technology for offshore platforms to indicate the percentage salinity levels in ice. From present experiment, it is also found that this technique is not useful to indicate the salinity level in water, however it do indicate the presence of salt in fresh water. These results are largely dependent upon the size of electrode plate, plate design and front dielectric panel material and thickness. Hence, optimizing the complete plate design can significantly improve the results. The electrode plate can be covered with different types of dielectric material much more resistant to harsh weather and climatic effects; since there are large number of thin dielectric materials available commercially nowadays. The weather resistant dielectric coating/covering can ensure the protection required to avoid corrosion of the plate. The low voltage requirement mV of the MEMS devices makes the design feasible for battery operated system in a remote location.

It was also quite difficult to delay the melting process of the saline ice sample (as the freezing temperature of saline ice is lower than fresh water ice) during experimentation. This problem was minimized by maintaining a temperature of $-5°C$ in the Cold Room Chamber (see Fig. 3) at Narvik University College.

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