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The effect of salinity and temperature on electromagnetic wave attenuation in brine

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ARTICLE INFO

Article history:

Received 26 September 2014

Received in revised form

25 November 2014

Accepted 30 November 2014

Available online 18 December 2014

Keywords:

Ice pigging

Ice fraction

Electromagnetic wave attenuation

Brine

Salinity

Temperature

ABSTRACT

Ice slurries are typically formed from an aqueous solution of water and salt (NaCl) at 5% salinity. Ice pigs, used in many industry areas, are taken from a bulk ice slurry and used to clear waste or recover product from pipes. Ice fraction is a key property of an ice slurry, since it determines its 'thickness' and therefore cleaning capacity. Electromagnetic wave interrogation has been shown to accurately predict an ice fraction to within an error of $\pm 1.2\%$. The largest remaining process error comes from inherent salinity variation, which affects the electromagnetic wave attenuation significantly. Increasing electromagnetic wave attenuation with increasing salinity and the effect of temperature, shown to also increase attenuation, is quantified. Calibration methods are proposed, aiming to eliminate the unwanted effect of varying salinity. Analysis on multiple samples showed a 16% reduction in average error, and 9% reduction in maximum error when the calibration method was applied.

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Effet de la salinité et de la température sur l'atténuation d'une onde magnétique dans la saumure

Mots clés : Raclage par coulis de glace ; Fraction de glace ; Atténuation de l'onde électromagnétique ; Saumure ; Salinité ; Température

1. Introduction

Previous work (Hales et al., July 2014) demonstrated that an ice slurry's ice fraction (by mass, ϕ_m) can be directly related to the electromagnetic (EM) wave attenuation in a sample. A method was devised, whereby an ice slurry sample of set width could be interrogated with EM waves ranging from 2.3 GHz to 2.7 GHz in a pipe. Analysis showed ϕ_m to be the dominating ice

slurry property on EM wave attenuation, but concluded that whilst brine salinity did not have a detrimental effect on the correlation, did create an error. Further research has shown temperature also has a profound on levels of EM wave attenuation in water based solutions, a variable not investigated in the research discussed above.

EM wave attenuation in ice is well understood, and negligible compared to losses in water solutions. When water freezes, impurities such as salt detach from the molecular

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<http://dx.doi.org/10.1016/j.ijrefrig.2014.11.013>

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Nomenclature

Φ_m	Ice fraction, by mass
ϵ_r^*	Complex dielectric constant
ϵ_r'	Real part of dielectric constant
L_f	Dielectric loss factor
C	Salinity
br	of brine
sam	of sample
id	ideal
exp	experimental
ϵ_s	Static permittivity
ϵ_∞	Optical permittivity
H_N	Average ion hydration number
λ	Wavelength
λ_s	Critical wavelength
$Abs_{\%}$	Electromagnetic wave absorption %
cm	per cm
W	per brine width
br	in brine
id	ideal
exp	experimental
Δ	error in
ADJ	adjusted
Rf_i	Reflected electromagnetic wave intensity
Tr_{max}	Maximum transmitted power intensity
W	Width
ice	of ice
br	of brine
sam	of sample

structure, meaning ice itself is unaffected by the composition of the solution it originated from, and is pure H₂O. However, in order to validate reliability of EM wave interrogation to find Φ_m , a clearer understanding of the relevant effects of salinity and temperature of brine is essential, and is investigated in this paper. Additionally, the paper proposes mathematical methods of eliminating the brine salinity variable from future EM wave interrogation trials.

In Section 2, the relationship between a water molecule's dipole moment and EM wave attenuation is discussed, as well as the effect on both with varying salinity and temperature. Additionally, previous experimental work and preliminary investigations are explained. The experimental apparatus and procedure are explained in Section 3, whilst the calculations to convert the raw data to meaningful results is covered in Section 4. Results are analysed to compare with the original hypotheses in Section 5, before being related to ice slurry diagnostics in Section 6, where brine salinity calibrations methods are proposed. Finally, key conclusions from the study are detailed in Section 7.

2. Theoretical background

EM wave attenuation occurs in water as the wave's photons excite the water molecules, causing them to rotate and absorb the photons' energy (Ruddy, 1986). A water molecule has a

dipole moment, the strength of which can be likened to it's dielectric constant, meaning it wants to align with the EM field (Pan et al., April 2013). The stronger the dipole moment, therefore, the stronger the water molecule's resistance to rotate and absorb EM wave energy. This is similar to the reasons behind very low EM wave attenuation in ice, where additional bonds in the molecular structure completely restrict molecule rotation (324719c1f8, 2013).

2.1. Factors affecting the dielectric constant

The addition of salt to water reduces the dielectric constant (and therefore the dipole moment), causing changes to the behaviour of EM waves in the resultant brine (Stogryn, 1971). The dielectric constant can be expressed as a complex number (ϵ_r^*), and is defined in Equation (1) (Chaplin, 2014), where ϵ_r' is the real part of the dielectric constant, describing a substance's ability to be polarised by an external field, and L_f is the loss factor.

$$\epsilon_r^* = \epsilon_r' - iL_f \quad (1)$$

Equation (2) (Chaplin, 2014) describes the factors affecting ϵ_r' . Taking the other coefficients as constants, an increase to salinity (C) directly relates to a decrease in ϵ_r' , and therefore ϵ_r^* . The other coefficients are static permittivity (ϵ_s), which is dependent on temperature, a constant for any given sample and discussed in further detail below; optical permittivity (ϵ_∞), relevant only for frequencies of EM wave near visible light and three constants: average hydration number of ions (H_N), wavelength (λ) and critical wavelength (λ_s).

$$\epsilon_r' = \frac{\epsilon_s - 2H_N C - \epsilon_\infty}{1 + \left(\frac{\lambda_s}{\lambda}\right)^2} + \epsilon_\infty \quad (2)$$

This relationship can be seen in Fig. 1, where an increase in salinity from 0‰ to 3.5‰ causes a drop in ϵ_r' , at 2.45 GHz. It is interesting to note that the effect of salt is most profound at temperatures around 0 °C, the region relevant to ice piggings.

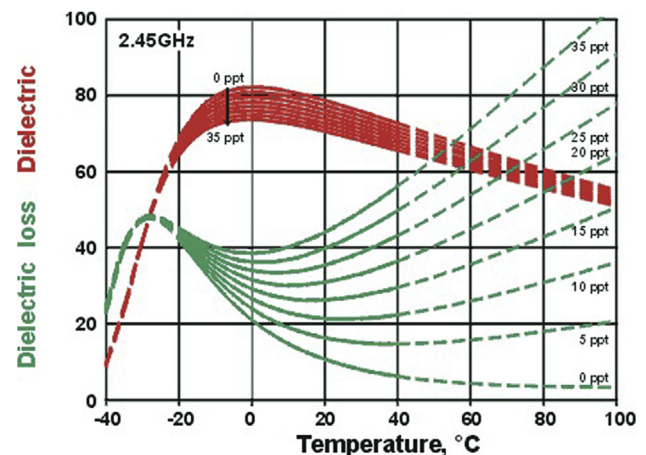


Fig. 1 – Effect on dielectric constant (red) and dielectric loss factor (green) in a range of brine salinities with an electromagnetic wave frequency of 2.45 GHz (Chaplin, 2014) (Meissner and Wentz, 2004). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

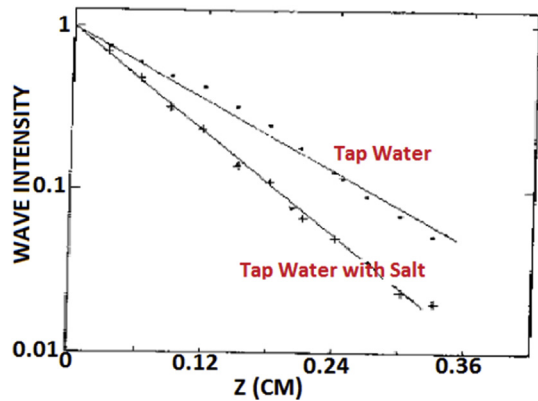


Fig. 2 – Distance into liquid vs. logarithmic EM wave intensity for tap water and brine (Haranas and Lonc, 1984).

Fig. 1 also shows the effect on L_f when salinity and temperature are varied. L_f decreases as temperature increases in pure water, eventually levelling out at a minimum. However, with any salt present, a stationary point occurs where L_f is lowest. This is down to the mobility of the freely moveable ions (in this case Na^+ and Cl^-) which increases with temperature, due to a reduction in fluid viscosity (Korson et al., 1969). An increase in ion mobility leads to an increase in fluid conductivity, a variable upon which L_f is dependent (Chaplin, 2014). As salinity is increased, the conductivity variable becomes more influential in affecting L_f , which can be seen in the position of the stationary point.

The stationary point occurs at decreasing temperatures as salinity is increased, up to the maximum salinity displayed on the graph, 3.5%, where it is located at approximately 0 °C. Through extrapolation of the provided data, it is reasonable to assume this stationary point will occur below the freezing points of brines with salinities of at least 5% (−2.8 °C), as is relevant to the ice pigging industry.

Furthermore, the relationship suggests the effect of temperature on L_f will become greater as salinity increases. The stationary point will move further into the negative temperature range, meaning the gradient of the curve will increase at freezing point.

Relating back to Equation (1), expected increase to L_f due to increasing temperature (when salinity is at least 5%) will relate to a drop in ϵ_r^* , and therefore an increase in EM wave attenuation.

It should be noted that the equations and graphical data discussed do not account for the presence of additional

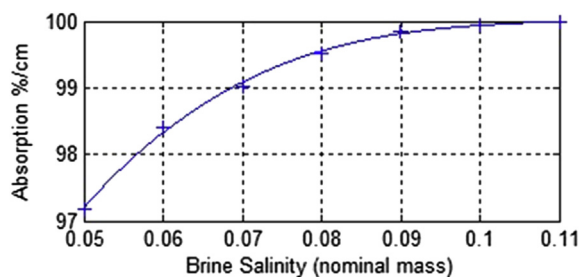


Fig. 3 – Salinity vs. electromagnetic wave absorption %/cm in chilled brine.

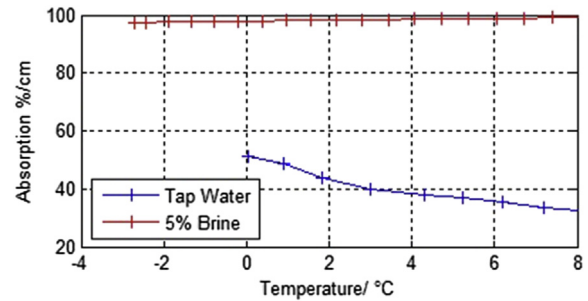


Fig. 4 – Temperature vs. electromagnetic wave absorption %/cm in tap water and brine with 5% (wt.) NaCl.

impurities in water, such as would be found at around 15 ppm in tap water. At this low concentration, general relationships governed by the equations are still reliable, but experimental work is essential to quantify the effects of salinity accurately. It is important that the focus remains on tap water, in order to stay relevant to the ice pigging industry.

2.2. Experimental studies on electromagnetic wave attenuation in brine

The effect of EM wave attenuation in brine was examined by Haranas and Lonc (Haranas and Lonc, 1984). In experimental work, EM waves at a frequency of 10 GHz were set up to propagate through a container, and wave intensity was measured at different distances into the contained liquid medium. Results are displayed for tap water, with and without added salt. The effect of salt, as expected, is to increase the EM wave absorption %/cm ($\text{Abs}_{\%,\text{cm}}$), as can be seen in Fig. 2.

Preliminary work was carried out, investigating the effect of varying salinity on EM wave attenuation in chilled brine at 2.45 GHz. The results, displayed in Fig. 3, show increasing $\text{Abs}_{\%,\text{cm}}$ with increasing salinity, further justifying the theoretical hypothesis.

A preliminary investigation was also carried out on tap water and brine, with a 5% concentration by weight of NaCl, in order to examine the relationship between temperature and EM wave attenuation. The results are displayed in Fig. 4. As expected, EM wave attenuation decreases with temperature without the presence of salt in the solution, but increases when 5% salt is present. Experiments in this

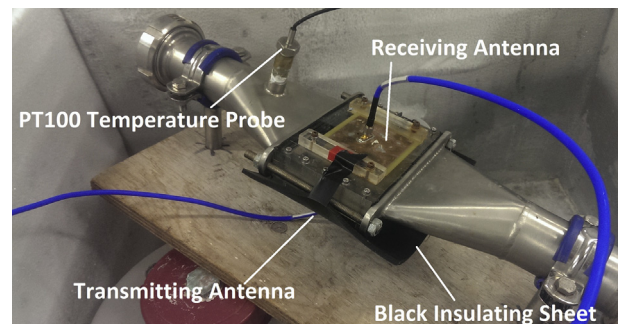


Fig. 5 – Annotated image of the experimental setup.

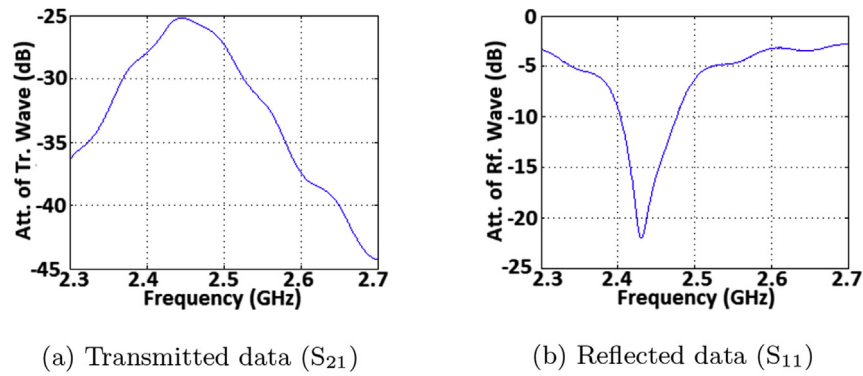


Fig. 6 – VNA example dataset: attenuation (dB) vs. electromagnetic wave frequency.

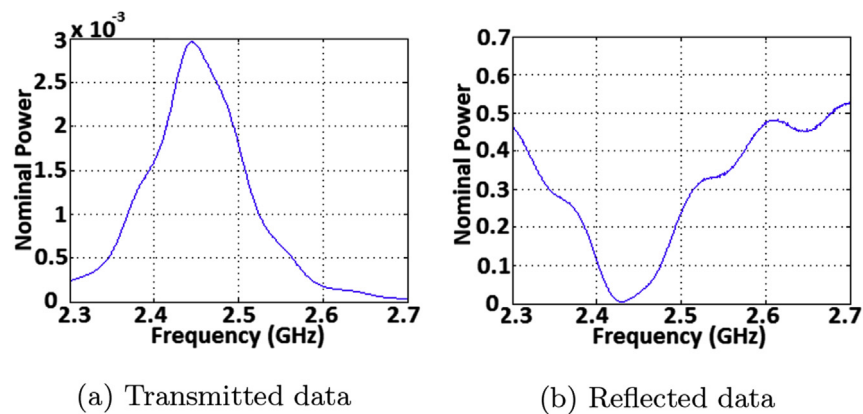


Fig. 7 – VNA example dataset: nominal power vs. electromagnetic wave frequency.

investigation did not use brine solutions with less than 5% salt, given its irrelevance to the ice pigging industry, so an increase in EM wave attenuation with an increase in salinity was expected.

3. Method

Trials were carried out investigating brine at varying concentrations, contained in the apparatus shown in Fig. 5. The

container itself had a volume of just over one litre, and its geometry allowed the interrogated area, of width 10 mm, to be centred around the solution mid height. This ensured that any stratification, due to varying salinity within a sample, would not have an effect on the concentration of the interrogated portion of the sample.

The container was placed inside a freezer and, once the brine was added, allowed to cool until the freezing point was reached. An EM wave scan ranging from 2.3 GHz to 2.7 GHz was carried out every five minutes for the duration of the trial

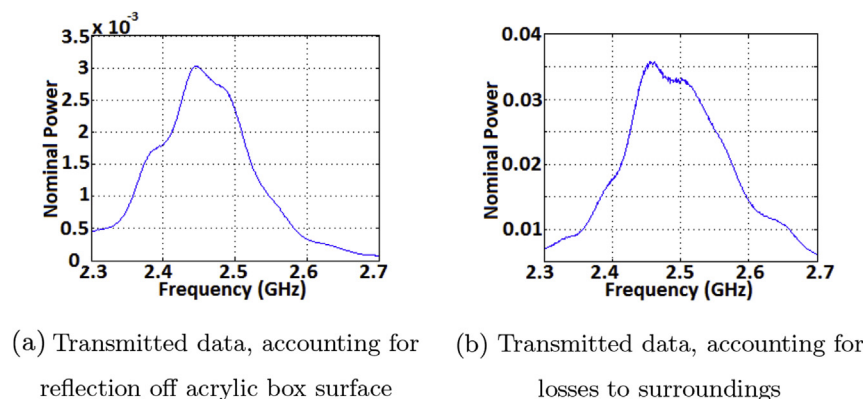


Fig. 8 – VNA example dataset: result calibration.

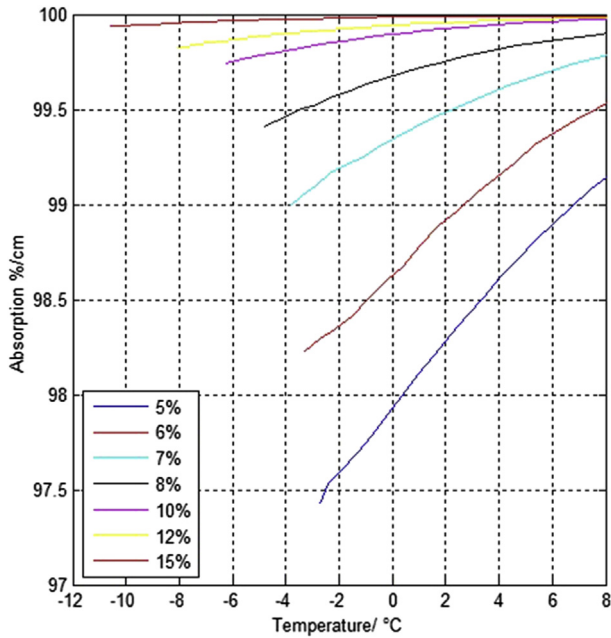


Fig. 9 – Temperature vs. absorption %/cm in cooling brine for a range of salinities.

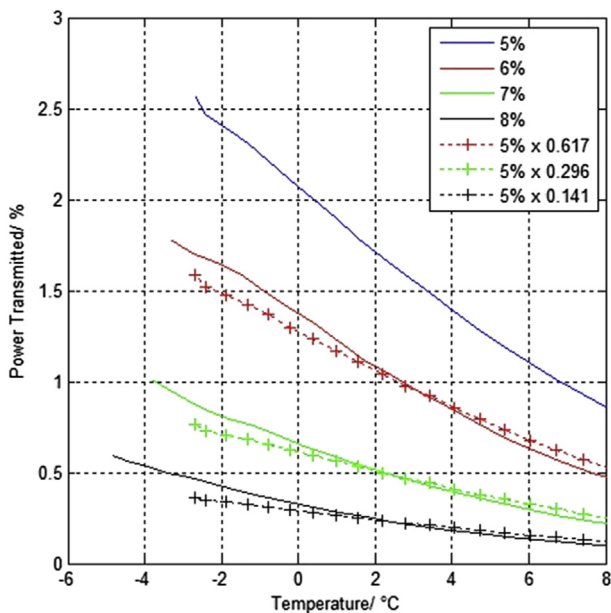


Fig. 10 – Temperature vs. transmitted power/% in cooling brine for a range of salinities.

using a VNA spectrum analyser and two antennas. This resulted in a dataset of 23 points for the 5% salinity sample, which increased to 31 points for the 15% sample, as the freezing point took longer to reach.

Repetition of trials was considered but eventually ruled out because of the additional complication of data extrapolation, given equivalent temperatures for each scan

Table 1 – Percentage of electromagnetic wave power transmitted through brine at various temperatures, for a range of salinities. $R_{5\%}$ refers to the average magnitude of power transmitted, compared to the equivalent value from the 5% dataset.

Salinity (%wt.)	% Power Transmitted at:						$R_{5\%}$
	–2 °C	0 °C	2 °C	4 °C	6 °C	8 °C	
5%	2.41	2.07	1.72	1.39	1.10	0.86	1
6%	1.64	1.37	1.08	0.85	0.63	0.47	0.617
7%	0.81	0.66	0.52	0.40	0.30	0.22	0.296
8%	0.42	0.32	0.25	0.18	0.14	0.10	0.141

would have been near impossible to achieve. The error as a result of this non-linear interpolation outweighed the benefits of multiple datasets, given the error between several 5% salinity sets during previous investigations was near negligible.

The signals were both produced and logged by the VNA spectrum analyser, and final S_{21} (transmitted signal) and S^{11} (reflected signal) data was taken for analysis. Typical examples of these datasets are shown in Fig. 6a, b. The manipulation of this raw data to produce values for $Abs_{\%,cm}$ in the medium is explained in Section 4.

Before each trial, a clear air scan was carried out, with the container and antennas in place. This control was used during the manipulation of the raw data to eliminate losses to the surrounds and reflections off the container wall interfaces. Additionally, two black insulating sheets were placed above and below the scanning area to absorb dispersing EM waves, so the receiving antenna was only picking up signals directly from the transmitting antenna and unaffected by reflection from the freezer walls.

The PT-100 temperature probe was monitored using a pico logger, and temperature was also taken every five minutes, at the start of each scan.

4. Calculations

The data taken from the VNA spectrum analyser relates to the signals shown in Fig. 6a, b. After converting both datasets from decibel attenuation to nominal power values (Fig. 7a, b), the transmitted power is re-calculated, to account for loss due to reflection off the surface of the acrylic box. This is done by assessing the reflected EM wave intensity, R_f from Fig. 7b, to find the maximum transmitted power intensity, $T_{r,max}$ (i.e. if no attenuation occurred, $1-R_f$) and finding the ratio of the two. An example of the resulting transmitted dataset can be seen in Fig. 8a.

Additionally, the transmitted data is compared to the control, clear air scan, to account for losses to the surroundings. Again, this was done through the ratios of the nominal powers across the whole frequency range. This manipulation lead to results such as the dataset shown in Fig. 8b. Maximum power intensity observed from each scan was recorded from these datasets, to be used for analysis.

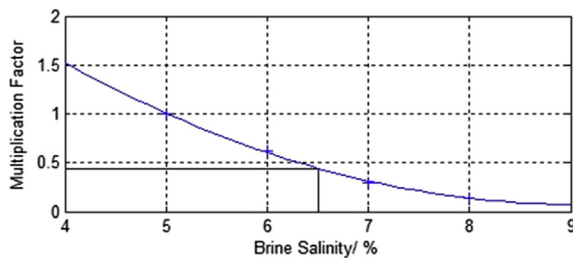


Fig. 11 – Brine salinity vs. multiplication factor to approximate electromagnetic wave attenuation, using 5% brine as a datum.

5. Results and analysis

5.1. Electromagnetic wave attenuation in brine

The final results from the investigation are displayed in Fig. 9, where the occurrence of both relationships discussed in Section 2. An increase in EM wave attenuation occurs with an increase in temperature and an increase in salinity.

The data can be further manipulated to show trends between the sets of results, in order to further analyse the relationship between EM wave attenuation and salinity in a cooling brine. Fig. 10 shows the power transmitted through the brine samples for salinities ranging from 5% to 8%. The datasets for 10%, 12% and 15% were not used, since the EM wave attenuation observed was too high, and errors in the remaining EM wave power would be large.

Average percentage power transmitted at the set temperatures for each salinity was also calculated, and given as a fraction in Table 1, compared to the average power transmitted through the 5% brine sample. The 5% dataset was then multiplied by each of these fractions in turn, the results of which can also be seen in Fig. 10. The 5% brine sample was used as the datum in this case as it is the usual bulk salinity for ice slurry in the ice pigging industry.

The manipulated 5% datasets show correlation with the datasets they are intended to represent, suggesting mathematical manipulation could be applied in future work to approximate the EM wave attenuation levels in brine across a range of salinities, to a reasonable level of accuracy. Fig. 11 shows a polynomial line of best fit devised from the samples' salinities and the multiplication fractions. As an example, the polynomial has been used to estimate the multiplication fraction necessary to approximate a dataset for a 6.5% brine sample. A fraction of 0.442 is suggested.

Returning to Fig. 10, it is important to note the error between the approximated datasets and the actual results. In

Table 2 – Power transmitted relative to at 0 °C, for various temperatures and a range of brine salinities.

Salinity (%wt.)	Power transmitted relative to 0 °C at:					
	–2 °C	0 °C	2 °C	4 °C	6 °C	8 °C
5%	1.16	1.00	0.83	0.67	0.53	0.42
6%	1.20	1.00	0.79	0.62	0.46	0.34
7%	1.23	1.00	0.79	0.61	0.45	0.33
8%	1.31	1.00	0.78	0.56	0.44	0.31

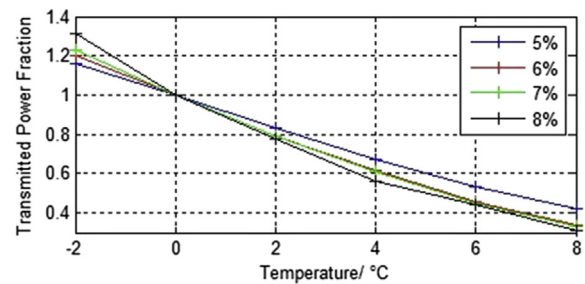


Fig. 12 – Temperature vs. transmitted power fraction for a range of brine salinities.

each case, EM wave power transmitted is over estimated at higher temperatures, and underestimated at lower temperatures. This would suggest temperature dependency on EM wave attenuation increases with salinity, as was predicted in Section 2.1. A small second order coefficient, used alongside the factor plotted in Fig. 11 could reduce this error significantly.

5.2. The effect of temperature on electromagnetic wave attenuation in brine

Table 2 is an adaption of Table 1, showing the power transmitted through each brine sample, compared to the power transmitted at 0 °C. This allows comparison of the EM wave attenuation dependency on temperature at different salinities. The data is shown graphically in Fig. 12. The plot confirms EM wave attenuation in brine samples is more susceptible to temperature change when higher concentrations of salt are present, as the gradient of the curve increases with increasing salinity.

6. Use of findings in the ice pigging industry

Data from this investigation has matched theoretical models with good correlation. This suggests EM wave attenuation in brine can be measured to a high level of accuracy.

Given success in the investigation, results were used to calibrate data from an experiment on ice slurry samples, with the aim of eliminating error due to uncontrollable changes to bulk salinity. The $Abs_{\%cm}$ data at the freezing point of each brine was plotted, and the resultant line of best fit is shown in Fig. 13.

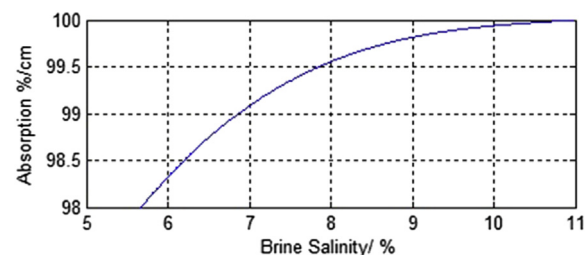


Fig. 13 – Brine salinity vs. EM wave absorption %/cm in brine at the freezing point.

For the experiment on ice slurry, it should be noted that ϕ_m was calculated via calorimetry and sample salinity was found using a densitometer on a 5 ml sample of the slurry tested in each trial, once all melting had occurred. The sample density was referred to relevant tables in the *CRC Handbook of Physics and Chemistry* (Lide, 2005).

ϕ_m was used to derive the brine salinity (C_{br}) from the sample salinity (C_{sam}), as shown in Equation (3). With the ice phase of the slurry eliminated, it was possible assess the effect of varying brine salinities.

$$C_{br} = \frac{C_{sam}}{\phi_m} \quad (3)$$

Ice width (W_{ice}) and brine width (W_{br}) are terms to describe the effective width of ice and brine an EM wave would have to pass through, from the transmitting antenna to the receiving antenna. Sample width (W_{sam}) defines the width of the scanning area, as in Equation (4). The manipulations in Equations (5) and (6) relate W_{br} to ϕ_m .

$$W_{sam} = W_{br} + W_{ice} \quad (4)$$

$$\phi_m = \frac{W_{sam} - W_{br}}{W_{sam}} = 1 - \frac{W_{br}}{W_{sam}} \quad (5)$$

$$W_{br} = W_{sam} \times (1 - \phi_m) \quad (6)$$

Fig. 14 graphically displays the relationship between C_{br} and W_{br} , with 5% sample salinity and a 1 cm sample width (as is standard with experimental work).

In order to recalibrate results, an ideal sample salinity ($C_{sam,id}$) was set to 5% and used to calculate an ideal brine salinity ($C_{br,id}$) for each trial, using Equation (7). These values are a normalised set of data to represent the brine salinities of each trial, had each experimental sample salinity ($C_{sam,exp}$) been 5%. The curve in Fig. 13 was used to relate this data to an ideal $Abs_{\%,cm}$ in brine value for each trial ($Abs_{\%,cm,br,id}$).

$$C_{id,br} = \frac{C_{id,sam}}{\phi_m} \quad (7)$$

An equivalent dataset, detailing the $Abs_{\%,cm}$ in brine using the experimental brine salinities ($Abs_{\%,cm,br,exp}$) is also necessary to find the error between actual and ideal $Abs_{\%,cm,br}$ values. As with the ideal salinity data, the trial brine salinities calculated from Equation (3) were related to the control $Abs_{\%,cm}$ values in Fig. 13.

The difference between experimental and ideal values for $Abs_{\%,cm}$ in brine ($Abs_{\%,cm,br,\Delta}$) was found using Equation (8).

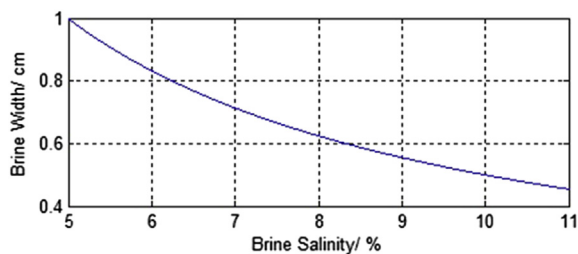


Fig. 14 – Brine salinity vs. brine width of an ice slurry at varying ice fractions (sample salinity: 0.05, sample width: 1 cm).

The data was then adjusted to represent the W_{br} from each trial (rather than a global/cm value), to give a calibration factor ($Abs_{\%,W,br,\Delta}$) for each trial, using Equation (9).

$$Abs_{\%,cm,br,\Delta} = Abs_{\%,cm,br,exp} - Abs_{\%,cm,br,id} \quad (8)$$

$$Abs_{\%,W,br,\Delta} = Abs_{\%,cm,br,\Delta} \times (1 - \phi_m) \quad (9)$$

Finally, the original dataset for $Abs_{\%,cm}$ in the ice slurry sample was recalibrated to create an adjusted dataset ($Abs_{\%,cm,Adj}$) using Equation (10).

$$Abs_{\%,cm,Adj} = Abs_{\%,cm} + Abs_{\%,W,br,\Delta} \quad (10)$$

Fig. 15 shows the original and recalibrated data from this experiment. The error in EM wave $Abs_{\%,cm}$ improves in seven out of the ten samples during the recalibration process, average error decreases by 16%, and maximum error drops by 9%. It should be noted that the drop in $Abs_{\%,cm}$ readings during calibration in each trial was expected, as the average sample salinity from the trials was calculated to be 5.26%, slightly higher than the control salinity of 5%.

7. Conclusions

The trials undertaken on cooling brine in this investigation have provided conclusive evidence that the relationship between a water molecule's dipole moment and EM wave attenuation can be observed during experimentation. Furthermore, the complex dielectric constant has been broken down to assess the individual effects of brine salinity and temperature.

Rising brine salinity has been shown to substantially increase EM wave attenuation in brine, and the magnitude of increase has been quantified, in order to model different data from differing salinities using a multiplication coefficient. Temperature has been shown to effect EM wave attenuation in water and brine as expected from the imaginary loss factor of the complex dielectric constant. With no salt present, EM wave attenuation decreases, but the presence of salt causes a change to the relationship and with a salinity of 5%, EM wave attenuation increases with temperature. EM wave attenuation becomes increasingly dependent on temperature as the salinity is further increased.

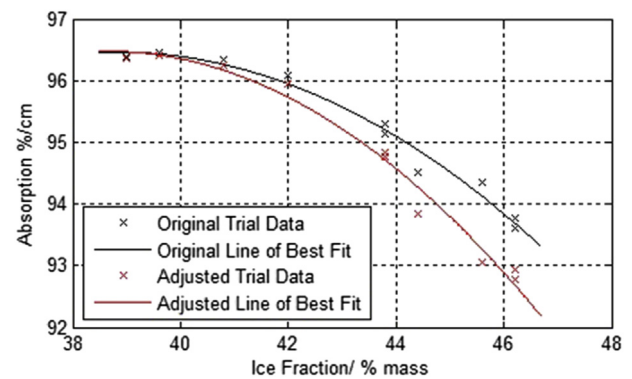


Fig. 15 – Ice fraction vs. EM wave absorption %/cm in ice slurry samples, before and after salinity calibration.

Given the success of the cooling brine trials, a method for accounting for varying salinity in ice slurry samples was derived and tested on an existing set of data. The process was shown to succeed in eliminating some error causes by the uncontrollable changes to brine salinity.

REFERENCES

- <http://www.thenakedscientists.com/html/content/kitchenscience/exp-/324719c1f8/>. [Accessed: 14/08/2013].
- M. Chaplin. Water and Microwaves. www1.lsbu.ac.uk/water/microwave. [Accessed: 16/09/2014].
- Hales, A., et al., July 2014. Ice fraction measurement of ice slurries through electromagnetic attenuation. *Int. J. Refrigeration* 46, 98–104.
- Haranas, Y.H., Lonc, W.P., 1984. Microwave attenuation in liquid media. *Am. J. Phys.* 52 (3).
- Korson, L., et al., 1969. Viscosity of water at various temperatures. *J. Phys. Chem.* 73 (1), 34–39.
- Lide, D.R., 2005. *CRC Handbook of Chemistry and Physics*, 86 ed. CRC Press, Boca Raton.
- Meissner, T., Wentz, F.J., 2004. The complex dielectric constant of pure and sea water from microwave satellite observations. *IEEE Trans. Geosci. Remote Sens.* 42 (9), 1836–1849.
- Pan, D., et al., April 2013. Dielectric properties of water under extreme conditions and transport of carbonates in the deep Earth. *Proc. Natl. Acad. Sci. U. S. A.* 110 (17), 6646–6650.
- Ruddy, D., 1986. *Microwave Technology*. Prentice-Hall Inc., Prentice Hall, New Jersey.
- Stogryn, A., 1971. Equations for calculating the dielectric constant of saline water. *IEEE Trans. Microw. Theory Tech.* 19 (8), 733–736.