ICE FRACTION ESTIMATION FOR ICE SLURRIES THROUGH IMPEDANCE MEASUREMENTS

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ABSTRACT

A new approach to ice concentration measurement for ice slurries is proposed and investigated in this work. The technique is based on in-line measuring of the impedance of an ice slurry flow. An impedance sensor was designed and built to conduct experiments. The sensor measures the impedance of the ice slurry flow in a frequency domain ranging from 20 to 120 kHz. Using this broad range of measurements, multiple parameters are determined which are then linked to the ice concentration. Ethanol is utilized as freezing point depressant. The initial ethanol concentration was varied from 3 to 6 wt-% and ice fractions from 0 to 50 wt-% were used. The ice concentration was also determined using temperature, density and calorimetric measurement. These other techniques were used as a reference and compared to the proposed impedance measurement technique. The measurement accuracy was shown to be at odds with the accuracy of the other measuring techniques. Other advantages of the proposed measuring method are the possibility to perform the measurement in-line and the low cost of the sensor.

INTRODUCTION

An ice slurry is a secondary refrigerant that can be used as an alternative to several other coolants. Ice slurries consist of a mixture of small ice crystals and a carrier fluid. This carrier fluid is a combination of water and a freezing point depressant. The use of ice slurries has several advantages when compared to traditional coolants [1]. The use of the latent heat of melting ice increases the energy density, while still being able to use pumps to transport the coolant. Furthermore, when made with non-harmful additives, for example salts or ethanol, ice slurries pose no potential threat to the environment. Finally, the possibility of storage for ice slurries has economic advantages: they can be produced during periods of low electrical power demand and stored until needed.

NOMENCLATURE

A	[m²]	Electrode surface area
C	[F]	Capacitance
D	[m]	Tube diameter
d	[m]	Distance
f	[Hz]	Frequency
j	[-]	Imaginary unit
L	[m]	Axial electrode length
R	[Ω]	Resistance
r	[m]	Shield radius
t	[m]	Tube wall thickness
x	[kg/kg]	Concentration
Z	[Ω]	Impedance
B	[°]	Electrode angle
ε_r	[-]	Dielectric constant
ε_0	[F/m]	Vacuum permittivity
ω	[rad/s]	Angular frequency

Subscripts

cf	Carrier fluid
eq	Equivalent
ice	Ice
is	Ice slurry
meas	Measuring
T	Tube wall
0	Initial

The ice concentration is an important parameter in the use of ice slurries. When a specified amount of cooling capacity is wanted, the adequate quantity of ice slurry has to be delivered. The energy density of ice slurries is dependent on the ice concentration [2]. The ice concentration or ice fraction is the ratio of the mass of ice particles in the solution to the total mass. It is therefore essential to be able to measure the ice concentration.

The goal of this work is to develop an accurate and inline ice concentration measurement technique. Many techniques already exist to measure the ice concentration [3], but all have their drawbacks. The three most common techniques are introduced and their limitations are discussed in the following paragraphs. Other techniques found in literature are either not applicable for the aim of this work or are still under investigation.

Calorimetric ice fraction measurement is based on adding heat to a batch sample. Based on the heat balance, the ice fraction can be calculated. This method is considered to be accurate to ± 1.5 wt-% [3]. However, this measurement technique requires a relatively large amount of time and cannot be performed in-line.

Temperature can be measured and related to the ice fraction, if the initial concentration is known. The carrier fluid is always at freezing point, which depends on the concentration of the additive [4]. This concentration together with the initial concentration can be used to calculate the ice fraction:

$$x_{ice} = 1 - \frac{x_0}{x_{cf}} \quad (1)$$

x_{ice} is the ice concentration, x_0 the initial additive concentration and x_{cf} the carrier fluid concentration. The main disadvantage of this measurement is the accuracy, especially for low initial additive concentration. The accuracy is reported to be ± 3 wt-% for an initial additive concentration of 20 wt-% and this uncertainty increases for decreasing concentrations [3].

In-line density measurement is another alternative to determine the ice fraction. The difference in density between the ice slurry and the separated carrier fluid is used to calculate the ice concentration. This method can determine the ice concentration within ± 2 wt-% if the density is determined within ± 0.15%. However, accurate in-line density meters are very expensive [3].

This work introduces impedance measurements as a fast, in-line and inexpensive alternative. The technique is based on the similar void fraction measurement for refrigerant flow [5]. The electrical capacitance of the ice slurry flow is derived from the impedance measurement. This capacitance varies with the ice concentration due to the difference in dielectric constant between two phases, in this case the liquid carrier fluid and the solid ice particles. Ice has a dielectric constant around 3 while water has a dielectric constant around 80 [6].

DESIGN OF THE CAPACITANCE SENSOR

A schematic representation of the impedance sensor is shown in Figure 1. The sensor consists of two concave electrodes (3) placed around an ice slurry flow (1). The electrodes are separated from the flow by a thin dielectric wall (2). Around the electrodes printed plastic parts (4) are added to maintain structural integrity. To shield the measurement from influences of the environment, a casing (5) is added around the construction. The empty space between the casing and the printed parts is filled with an epoxy resin (4), which will make the ensemble robust and leak-free.

There are several design parameters, among which those shown in Figure 1. These parameters are chosen to acquire a good correlation between the ice concentration and the capacitance of the ice slurry flow which is derived from the measurement. To analyse the influence of the design parameters, finite element simulations were performed to determine the electrostatic field. The capacitance is calculated from the simulations and the results are used to investigate the influence of the different parameters.

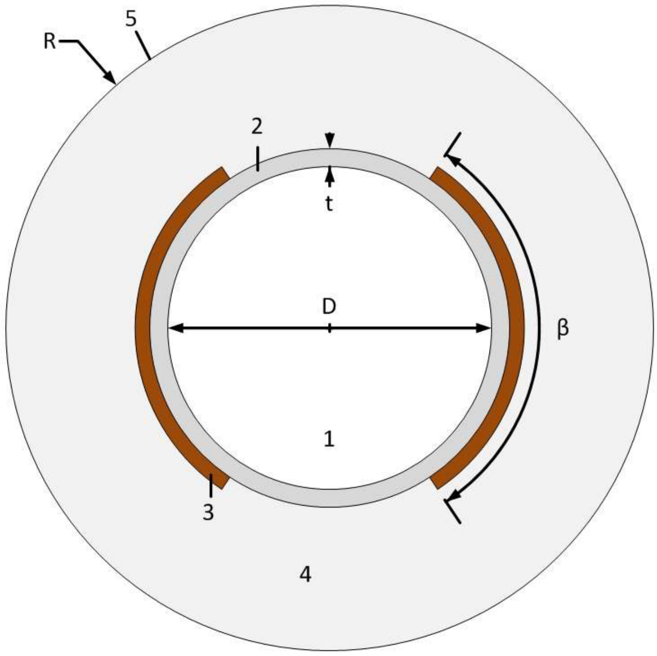

Figure 1 Cross-section of the measuring capacitor

Determination of design parameters

The design parameters are the tube diameter D, the wall thickness t, the shield radius r, the electrode angle β and the axial electrode length L. The influence of these parameters is discussed in the following paragraphs.

Varying the tube diameter D has no influence on the measurement. The surface of the electrodes increases, but the distance between then will increase accordingly. This causes the capacitance to remain the same. Intuitively, this result can also be derived from equation 2. This equation determines the capacitance of a parallel-plate capacitor:

$$C = \varepsilon_r \varepsilon_0 \frac{A}{d} \quad (2)$$

In this equation, ε_r is the dielectric constant of the dielectric material between the plates, ε_0 is the vacuum permittivity, A is the surface area of the electrodes and d is the distance between the electrodes. If the distance between the electrodes and the electrode area are increased with the same factor, the capacitance will remain constant.

The tube wall will create an extra capacitance in series with the capacitance of the flow. If the capacitance of the tube wall becomes too small, a variation in the capacitance of the ice slurry flow will have a small, non-measurable effect on the output. To avoid this, the capacitance of the tube wall should be as large as possible, so its thickness t has to be very small [7].

The simulations show that a variation in the shield radius r has a small effect on the measurement. When the shield is closer to the electrodes, the electric flux between both electrodes that travels outside the tube will be smaller. This will cause the capacitance of the outside of the tube to be smaller and to have less effect on the measurement.

The electrode angle β affects the measurement in several ways. When the angle becomes very large (just below 180°), the influence of the tips of the electrodes becomes large. This is because the distance between the electrode tips becomes very small. As a result, the local distribution of ice particles at the top and bottom influences the measurement greatly. This causes the sensor to be very sensitive to local variations and it will not give a correct representation of the ice concentration of the entire flow. On the other hand, when the angle becomes small, the axial electrode length will have to increase to obtain a large enough electrode surface. The capacitance is directly proportional to the electrode surface. So to obtain a capacitance that is large enough to be measured with a sufficient accuracy, a large enough surface is needed. For low electrode angles, the length will be too large to make a compact sensor. The simulations show that an angle of 100° is a suitable compromise and has a near linear relation between ice fraction and capacitance.

When the angle is known, the axial length L, which is the length of the electrode in the direction of the flow, can be chosen to obtain the desired range for measured capacitance. All the determined parameters are summarized in Table 1.

Table 1 Design parameters for capacitance sensor

D	t	r	L	β
40 mm	0.1 mm	37.5 mm	160 mm	100°

Influence of initial additive concentration

The initial additive concentration of the mixture used to make ice slurries can be varied. It is desirable to be able to determine the ice concentration of the ice slurry flow without having knowledge of the initial additive concentration. To achieve this, the ice concentration measurement has to be independent of the initial additive concentration. However, the concentration of additives such as ethanol and ethylene glycol has an influence on the dielectric constant of the mixture. This means the capacitance will vary with the initial additive concentration. The ice slurries studied in this work are made with ethanol as additive and with initial concentrations varying from 2 wt-% to 6.5 wt-%. The dielectric constant of mixtures of water and ethanol are determined by [8]. Finite element analysis showed that the varying initial ethanol concentration resulted in a deviation of the ice concentration measurement of ± 0.5 wt-%, which is acceptable.

EQUIVALENT ELECTRICAL MODEL

The impedance sensor can be represented electrically by an equivalent electrical model. This model is shown in Figure 2. Analysis of this model is needed to determine the influence of the conductivity of the ice slurry on the measurement. The conductivity of the ice slurry flow is dependent on the ice concentration, the initial additive concentration and the purity of the water used to make the ice slurry. Because the ice concentration measurement should be independent of the initial additive concentration and the type of water used, it has to be independent of the conductivity.

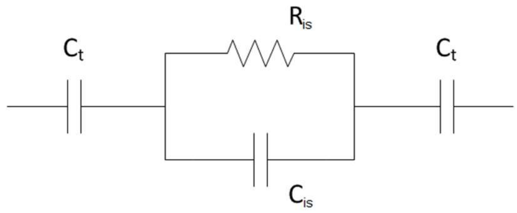

Figure 2 Equivalent electrical model

The model shows the electrical representation of the dielectric wall and the ice slurry flow. The dielectric wall on either side of the ice slurry flow does not conduct electricity, but acts as a capacitor. This is modelled as C_t on the left and right in Figure 2. The ice slurry flow acts as a capacitor, but also conducts electricity. The ice slurry flow is thus modelled as a capacitor C_{is} in parallel with a resistor R_{is}.

The impedance $\overline{Z}$ of this model can be derived as:

$$\overline{Z} = \frac{1 + j\omega R_{is}(C_{is} + C_t/2)}{j\omega C_t/2\,(j\omega R_{is}C_{is} + 1)} \tag{3}$$

ω is the angular frequency, j is the imaginary unit. For low frequencies the model acts as the two tube wall capacities in series. The impedance becomes independent of the capacitance of the ice slurry flow, making it impossible to derive the ice concentration. In the mid-range frequencies, the impedance of the model becomes partly resistive and its magnitude becomes dependent on the ice slurry resistivity. For high frequencies it acts again as a true capacitor, but now as the series connection of both tube wall capacities and the ice slurry capacitance. For these frequencies, the impedance is thus independent of the resistivity.

The conclusion is that the magnitude of the impedance cannot always be directly related to the ice concentration. It is necessary to derive the ice slurry capacitance from the impedance, since the impedance itself can be strongly influenced by the concentration of the additives and the purity of the water.

To visualise the influence of the frequency on the equivalent electrical model, an equivalent capacitance C'_{eq} is plotted in function of the frequency in Figure 3. This equivalent capacitance is derived from the impedance using equation (4):

$$C'_{eq} = -\frac{1}{\omega\left|\overline{Z}\right|} \tag{4}$$

Model validation

To validate this model, measurements were done on a test setup, similar to the designed impedance sensor. A parallel plate capacitor was made. Two aluminium plates are separated by a fluid contained by a thin plastic layer. The plastic layer is the equivalent for the tube wall in the sensor.

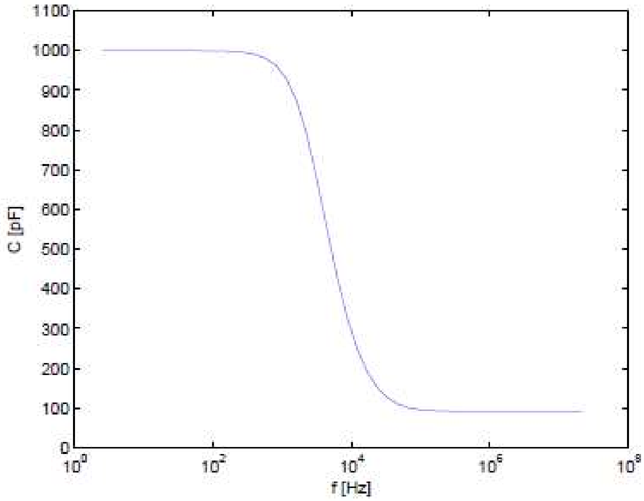

Figure 3 Equivalent capacitance of the electrical model for C_t=2000pF; C_{is}=100pF; R_{is}=50000Ω

A frequency generator is used to acquire voltage waves with a desired amplitude and of different frequencies. The amplitude of the current through the system is measured and with this the value of the magnitude of the impedance Z is calculated. The equivalent capacitance C'_{eq} is derived from this magnitude using equation (4).

Measurements are done with two mixtures of water and ethanol with different concentrations. The measurements are illustrated in Figure 4. The figure shows the equivalent capacitance in function of the measuring frequency. The parameters of the electrical model are fitted to the measurements. The resulting model with the fitted parameters is also shown on the figure. It shows good agreement with the measurements for both tested fluids.

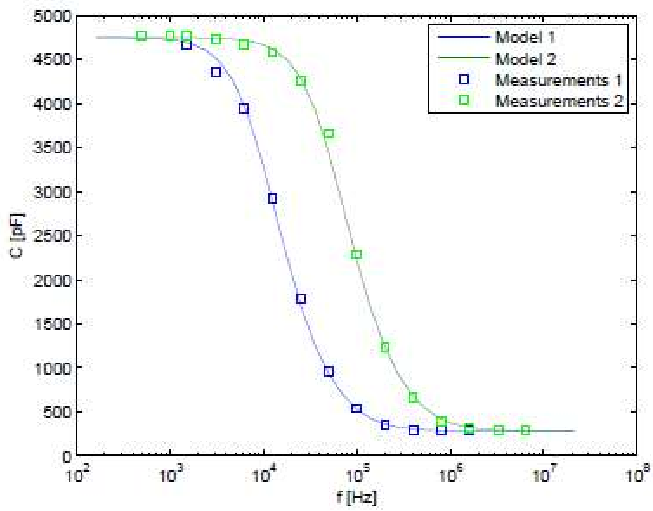

Figure 4 Measurements fitted to the model with C_t=9500pF; C_{is}=300pF; R_{is1}=3300Ω; R_{is2}=600Ω

MEASUREMENTS AND RESULTS

A test setup was created which pumped ice slurry through the sensor. The ice slurry was produced using the Deepchill ice generator by Sunwell. The ice generator creates ice slurry by cooling and freezing the fluid at the walls. The layer of ice formed against the wall is continuously removed by a scraper to create ice particles. After creating ice slurry, measurements are performed. Then the ice slurry is cooled further, which increases the ice concentration. The measurements are repeated and again the ice slurry is cooled further. This process is repeated until the ice generator reaches its limit. The entire method is repeated several times for different initial ethanol concentrations.

Reference measurements

Aside from the impedance measurement, three reference measurements are conducted to calibrate the sensor and to compare the accuracies: a temperature, density and calorimetric measurement. All three measurement techniques require knowledge of the initial ethanol concentration. This is determined using a density measurement. The density meter used was the DE40 by Mettler Toledo. The device measures with an accuracy of 0.0001 g/cm³.

Temperature was measured with Testo 735-1 measuring device in combination with a Pt100 probe. This device has an accuracy of ± 0.05 °C. The ice fraction determined with this technique had a minimum accuracy of ± 3 wt-%.

The density measurement was achieved by separating the carrier fluid from the ice particles. The carrier fluid density is measured and related to the carrier fluid concentration. Using equation (1), the ice fraction is determined. Determining the ice concentration with this technique has a minimum accuracy of ± 2 wt-%.

The calorimetric technique is done by taking a batch of ice slurry. The mass and temperature are measured. Next it is mixed with a heated up mixture which has the same ethanol concentration. The temperature of the heated mixture is also determined. After mixing and melting of all the ice, the temperature and the mass of the mixture are determined. All these values are used to calculate the ice fraction from the heat balance. The calculated ice fraction has a theoretical minimum accuracy of ± 1.3 wt-%. However, there are extra uncertainties due to parasitic heat flows which are not taken into account in the calculations, resulting in a lower accuracy than the density measurement technique.

Figure 5 shows the results of the three measurements for an ethanol concentration of 4.0 wt-%. It is clear that the measurements do not completely agree, this is due to not being able to perform all measurements at the exact same time. The density-based measurement is the most accurate and therefore chosen as reference measurement for the capacitance sensor.

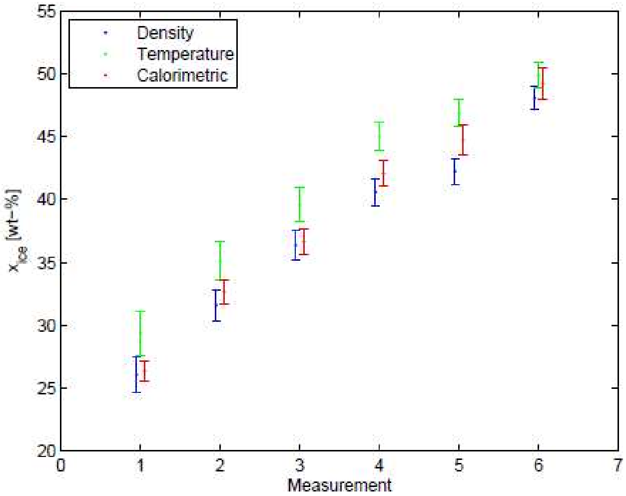

Figure 5 Temperature, density and calorimetric measurement

Impedance measurement method

Two different methods of measuring the impedance were used.

The first method uses a transducer which is based on the work of Yang [9] and the modifications by Canière [10], where it is used to measure capacitances. In this case, the transducer measures the magnitude of the impedance instead. The measuring circuit uses a charge/discharge method. A square voltage signal with a certain frequency (the measuring frequency) is applied to the impedance. The resulting current that flows through the impedance is proportional to the magnitude of the impedance. The current is converted to a voltage, which is directly proportional to the magnitude of the impedance.

For high frequencies, the magnitude of the impedance is independent of the resistivity of the ice slurry flow, as derived in section 3. This results in the measurement being independent of the initial ethanol concentration. However, when varying the ethanol concentration, the measurements did not correspond, even for the highest measuring frequency possible for the transducer. It was concluded that since the measuring frequency could not be increased further, the influence of the resistivity could not be eliminated with this transducer.

Therefore, another method is developed to determine the ice concentration. This second method measures the magnitude and the phase of the impedance over a frequency interval ranging from 20 kHz to 120 kHz. This is done by applying a sine voltage wave with a desired amplitude and frequency and measuring the amplitude and the phase shift of the current. The equivalent electrical model is fitted to the measurements and in this way the parameters of the model are determined. The fitting of the model to a measurement is shown in Figure 6. The equivalent resistance R_{eq} and capacitance C_{eq} in this case are determined as:

$$R_{eq} = \mathrm{Re}(\bar{Z}) \quad (5)$$

$$C_{eq} = -\frac{1}{\omega \, \mathrm{Im}(\bar{Z})} \quad (6)$$

Figure 7 shows the determined ice slurry capacitance in function of the ice concentration for two different initial ethanol concentrations. It is clear that these determined values are independent of the initial ethanol concentration. With the new method, the determined capacitance can be related to the ice concentration through a reference curve. The measurements indicate that the accuracy is at least as good as the accuracy of the reference density measurement, which is about ± 2 wt-%.

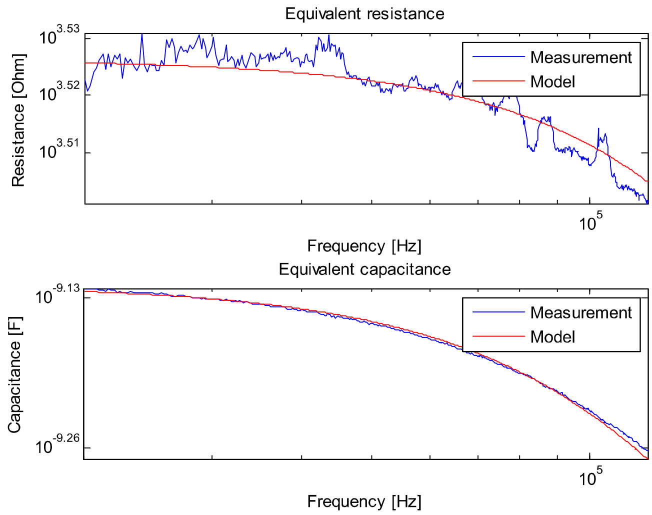

Figure 6 Measurements and model of the equivalent resistance and capacitance in function of frequency

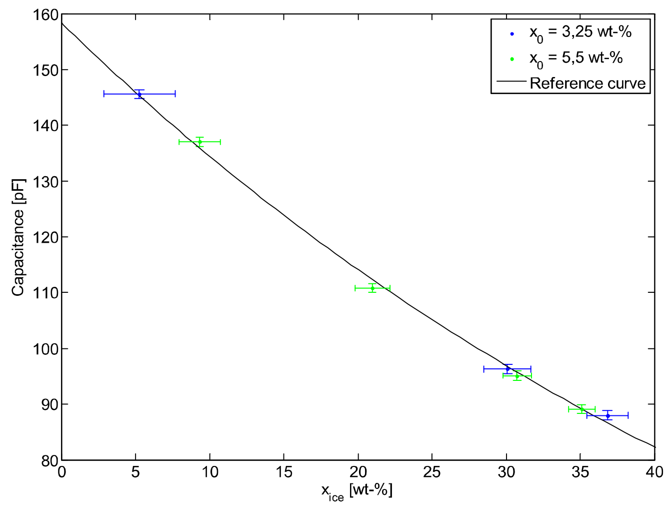

Figure 7 Capacitance in function of ice concentration for different initial ethanol concentrations

CONCLUSION

To perform in-line ice fraction measurements, traditional methods fall short. Temperature measurement is too inaccurate, density measurement too expensive and calorimetric measurement cannot be performed inline. An impedance sensor for ice concentration measurement is introduced. A design was made using simulations to determine the sensor dimensions. The influence of the resistivity and the measuring frequency is identified using an equivalent electrical model. The measurement is independent of flow velocity and initial ethanol concentration, can be done inline and the sensor is inexpensive. The impedance meter has been shown to determine the ice fraction with an accuracy of at least ± 2 wt-%.

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