Sensors For Contactless Estimation Of Ice Concentration In "Ice Slurry" Fluids

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Abstract – This paper deals with the problem of estimating the ice fraction in ice slurry fluids flowing into the pipes of industrial refrigeration apparatus based on secondary refrigerants. Such measurements must be performed in a non invasive way and the sensors must face with severe environmental conditions.

Two different sensors have been developed and are presented here. In particular, an optical sensor is presented that relates the transmission of signals with the ice density, while a capacitive sensor is proposed as well exploiting the effects of ice particles concentration on the ice slurry fluid permittivity.

Experimental prototypes have been realized for each one of the sensors proposed here. These sensors have been applied to an experimental refrigeration system that allows obtaining different percentage of ice in a controlled and reproducible manner. The experimental results obtained for each one of the sensors are reported showing the suitability of the approach. Some conclusive remarks are also given in order to compare the sensor performances.

I. Introduction

Secondary refrigerant refrigeration apparatus can significantly profit of using two phase secondary refrigerants, based on water with suitable additives, where a certain quantity of ice particles comes with the decreasing of temperature. Such fluids, called "ice slurries", allow extracting heat from an end user without significantly increasing their temperature; therefore they present a very high thermal efficiency [1].

However the pumps used to circulate the fluid into the pipes all around the refrigeration system, must work on a fluid having a much higher viscosity due to the presence of ice particles, and thus the overall efficiency of the refrigeration system is reduced due to the larger power demand of the pumps. Such an efficiency reduction can become relevant, especially if large industrial refrigeration plants are considered, and therefore the regulation of the ice percentage in the pumped fluid must be performed trying to match the requirement of high thermal efficiency with the conflicting one of low power consumption in the pumps.

Sensors for the estimation of ice concentration are therefore needed.

It is moreover important that the sensor works without getting in touch with the fluid. In fact ice slurries are generally made by a mixture of water and some additives (glycol, potassium formate, etc.) that fix the freezing point of the solution but also define the viscosity and thermal properties of the resulting fluid [2]. Contact less measurement strategies must be therefore planned that allows therefore neglecting any possible effect of the additives on the sensor.

Moreover, taking into account the ice slurry flowing inside the pipes of the refrigeration system, the insertion of any external element (the sensor) is not recommended; in fact it could produce agglomeration of ice thus perturbing the fluid and producing non equilibrium thermal conditions.

II. The Sensors Developed

A. Capacitive sensor

The presence of ice particles into a fluid will reflect into changes in its electric parameters and in particular measurements of the dielectric properties will allow for estimating the ice fraction. This is the idea that has guided to the development of the sensors presented in this section.

The capacitive contribution of the two part constituting the fluid, liquid and ice, can be modeled as [3]:

$$\frac{1}{C_{total}} = \frac{1}{C_{liquid}} + \frac{1}{C_{ice\ particles}} \qquad (1)$$

The total capacitance can also be expressed as:

$$C_{total}(\rho,\omega) = K\varepsilon_0\left[\varepsilon^{'}(\rho,\omega) - i\frac{\sigma(\rho,\omega)}{\omega\varepsilon_0}\right] \qquad (2)$$

where ρ represents the conductivity of the fluid, K represents the proportionality coefficient between capacitance and permittivity related to geometrical quantities and ω is the signal frequency.
A change in the capacitance value can be therefore predicted for variations both in the fluid permittivity and in its conductivity. The capacitive sensor proposed here is based on the Heerentz geometry [4] shown in the next Fig.1a.

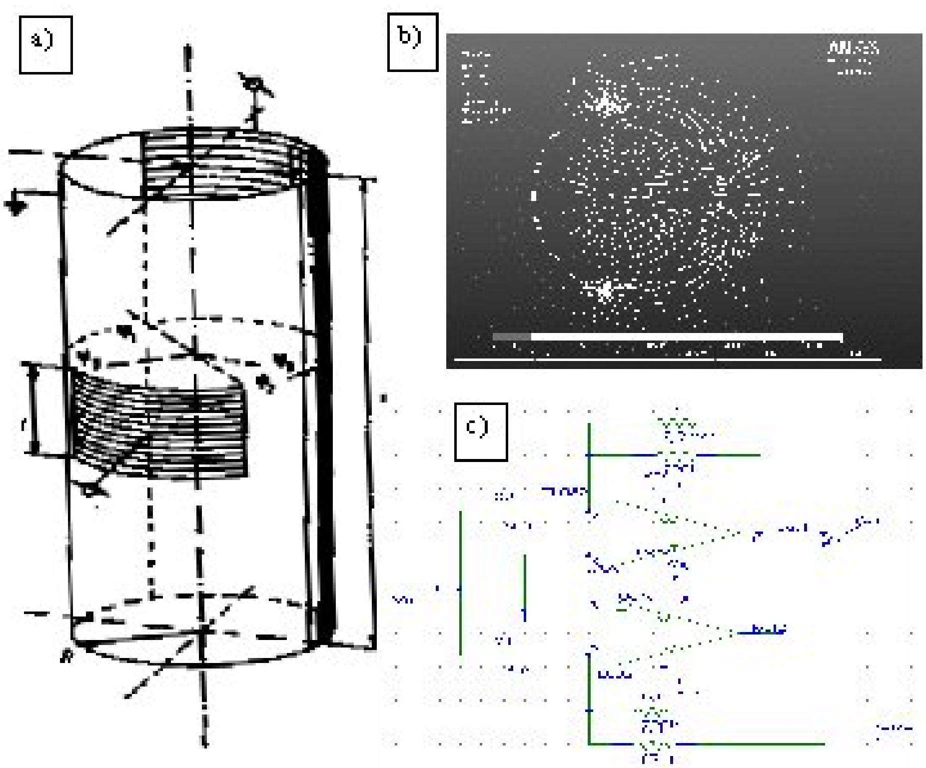

Figure1. a) The Heerentz geometry for the capacitive sensor proposed. b) Electric field lines over a transversal section of the capacitive sensor. c) The conditioning circuit schematic.

This capacitive sensor is modeled by the following equation:

$$C = \frac{\varepsilon_0\varepsilon_r}{\pi}\mathrm{K} \qquad (3)$$

where the parameter K descends from the quantities shown in Figure 1 as:

$$\mathrm{K} = \ln\frac{\sin\left(\frac{\Phi_3-\Phi_0}{2}\right)\sin\left(\frac{\Phi_2-\Phi_1}{2}\right)}{\sin\left(\frac{\Phi_2-\Phi_0}{2}\right)\sin\left(\frac{\Phi_3-\Phi_1}{2}\right)} \qquad (4)$$

In order to optimally define the electrodes geometry, taking into account also the dimension and the material of the pipe, a Finite Element Method analysis has been performed. In the following Figure 1b one example of the obtained electric field distribution is shown. A capacitive bridge has been finally used to convert the capacitance value to an output voltage signal [5]. The circuit schematic is shown in Figure 1c.

The output voltage depends on the sensor capacitance value C_2 in accordance with the following relation:

$$V_1 = -\frac{s(C_1R_3 + \alpha C_2R_2)R_1R_4}{\alpha R_2R_1 + R_3R_4}V_s \tag{5}$$

where C_1 is a fixed capacitor and Vs is the excitation signal.

B. Optical sensor

Instead of characterizing the electrical properties of the ice slurry as a function of ice concentration, it could be possible to exploit other properties that are related to the presence of ice particles such as optical absorbance or equivalent density.
In particular an optical transducer has been developed by using a couple of "wavelength coupled" photo diode and photo transistor (working in the near infrared region). The wavelength has been chosen taking into account the absorption properties of ice that is the element to be sensed. The optical transducers have been placed on the opposite sides of a transparent section of the pipe and the transmitted power has been recorded for various working conditions.

III. Experimental Prototypes And Results

In order to perform sensors characterization, an experimental refrigeration apparatus has been developed. It is based on a refrigeration unit that produces the ice slurry, a pump, a pipe of suitable length and a heat exchanger. This experimental apparatus is shown in Figure 2; moreover the sensor prototypes are shown in the same figure.

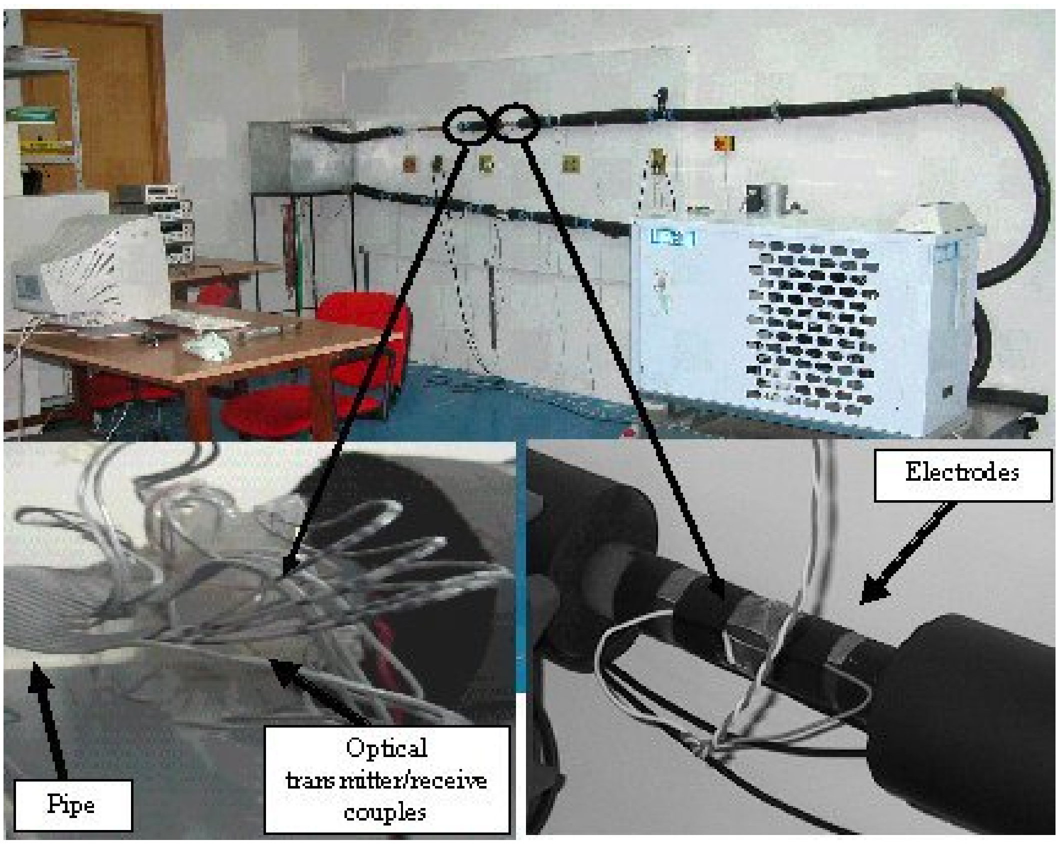

Figure 2. The experimental apparatus for producing ice slurry. It is possible to see the refrigeration unit, the pipe with the different sensors inserted and the heat exchanger. Bottom left, picture of the optical transducer, bottom right the capacitive transducer.

This apparatus allows producing ice slurry in reproducible conditions such to have a thermal equilibrium in the fluid. In this case the ice content percentage for a given mixture can be obtained from the freezing curve characteristic once the fluid temperature is known [2].
Experimental characterization of the sensors has been performed, in particular in the following some pictures of the prototypes realized are reported together with the experimental results obtained.
The experiments have been performed with mixtures of water and glycol for applications at -5 °C. Therefore the freezing point of the fluid has been settled at -3.5 °C such to span ice concentration values up to 20% with the lowest values of the temperatures obtained.
The experimental results are reported in Figure 3.
In particular in the case of capacitive transducer, in Figure 3a it can be seen as the output voltages (both V1 and V2 of the conditioning circuits are reported) monotonically change with the temperature lowering. Referring to non electrical properties of the ice slurry, in the Figure 3b the experimental results are reported in the case of the optical sensor. In this case it is evident as the light absorption increases with the presence of ice; in fact the transmitted signal greatly decreases while lowering temperature without a corresponding increase in the reflected signals (also reported in the lower part of the same Figure 3b).

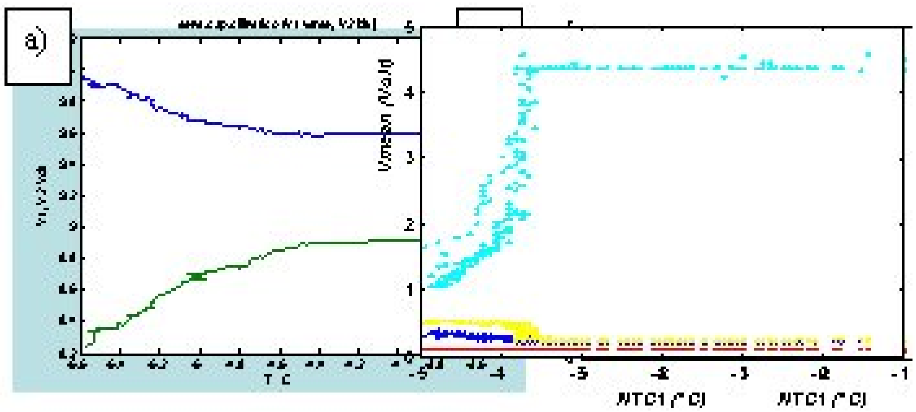

Figure 3. a) d) Experimental results for the capacitive sensor; b) Experimental for the optical sensor. It is evident as the absorption increases with the presence of ice.

IV. Conclusions

The problem of estimating the ice fraction in ice slurry fluids has been faced in this paper. To this aim two different sensors have been realized that exploit different working principles.
Both electrical properties and non electrical properties of the fluid considered have been characterized. In particular the fluid permittivity has been related to the ice concentration by using a capacitive sensor as well as the optical absorption changes with the ice particle concentration has been considered by using an optical transducer.
All the sensors developed give reliable results, however some considerations must be done in order to compare their performances.
Such a comparison must be made taking into account several different parameters related to the industrial application of the sensors. In fact quantities such as power consumption, noise immunity must be considered together with cost and robustness. Sensitivity is a critical issue but also it would be greatly appreciable if the sensor output would be not dependent on the additives used in the fluid but only on the ice particles concentration.
This latter feature is presented by the optical transducers that also has a good sensitivity; while from a power consumption point of view it appears more suitable the capacitive solution. Therefore the final choice will be driven by the need of benchmarking all the constraints.

Acknowledgments

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