2018

Concentration Measurement of Refrigerant/ Lubricant Mixture

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Concentration measurement of refrigerant/lubricant mixture by capacitive sensor

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ABSTRACT

The solubility of refrigerants in the lubricant is a key factor for the life time of a compressor with the new Low Global Warming Potential (LGWP) refrigerants showing generally higher solubility in lubricants than current refrigerants. During compressor operation, it is important to compare the dilution changes in the oil sump due to refrigerant properties to ensure proper lubrication of the bearings, and sampling is a measurement method that is commonly used to do this. However, this method can be time consuming, disturbs system behaviour and requires additional security precautions when sampling flammable refrigerants.

This paper presents a new measurement method based on the permittivity properties of fluids and their mixtures. The investigations consider the use of HFC, HC, HFO and their blends. In most of the cases presented, the method used delivers satisfying results, but care should be taken for some fluids that exhibit polar properties.

Measurements of viscosity and dilution in the oil sump of a compressor using this new method are presented here. Using a linear mixing rule for relative permittivity, the experimental data showed a very good correlation with sampling and PTVS curves (Daniel plots) when running at stabilized conditions. This method does not disturb system behaviour and decreases the time needed for the experiment.

1. INTRODUCTION

Recent developments in regulations governing the use of refrigerants with respect to their global warming potential (Europe F-GAS regulation) imply the introduction of new refrigerants and the adequate lubricant for these new applications. These new refrigerants tend to be more soluble in the lubricant thereby increasing reliability risks of the compressors.

Consequently, tests with new LGWP refrigerants have been performed where the dilution of the refrigerant in the sump lubricant was evaluated based on relative permittivity measurement of the mixture in the sump. This dilution evaluation was performed on a standard compressor at different saturated suction temperatures and superheat conditions which cover the range of compressor applications.

On Figure 1 is presented a compressor operation map showing classic running conditions areas. On the lower part of this Figure 1, for several couples of refrigerant and lubricant, is shown the refrigerant dilution (%wt) in lubricant and the resulting viscosity (cSt) of some applications. It highlights the important variations of lubricant properties across the whole applications range, hence the need to evaluate in more details the impact of the new refrigerants used.

This article presents the method used and the results of the tests which were then compared to the usual methods.

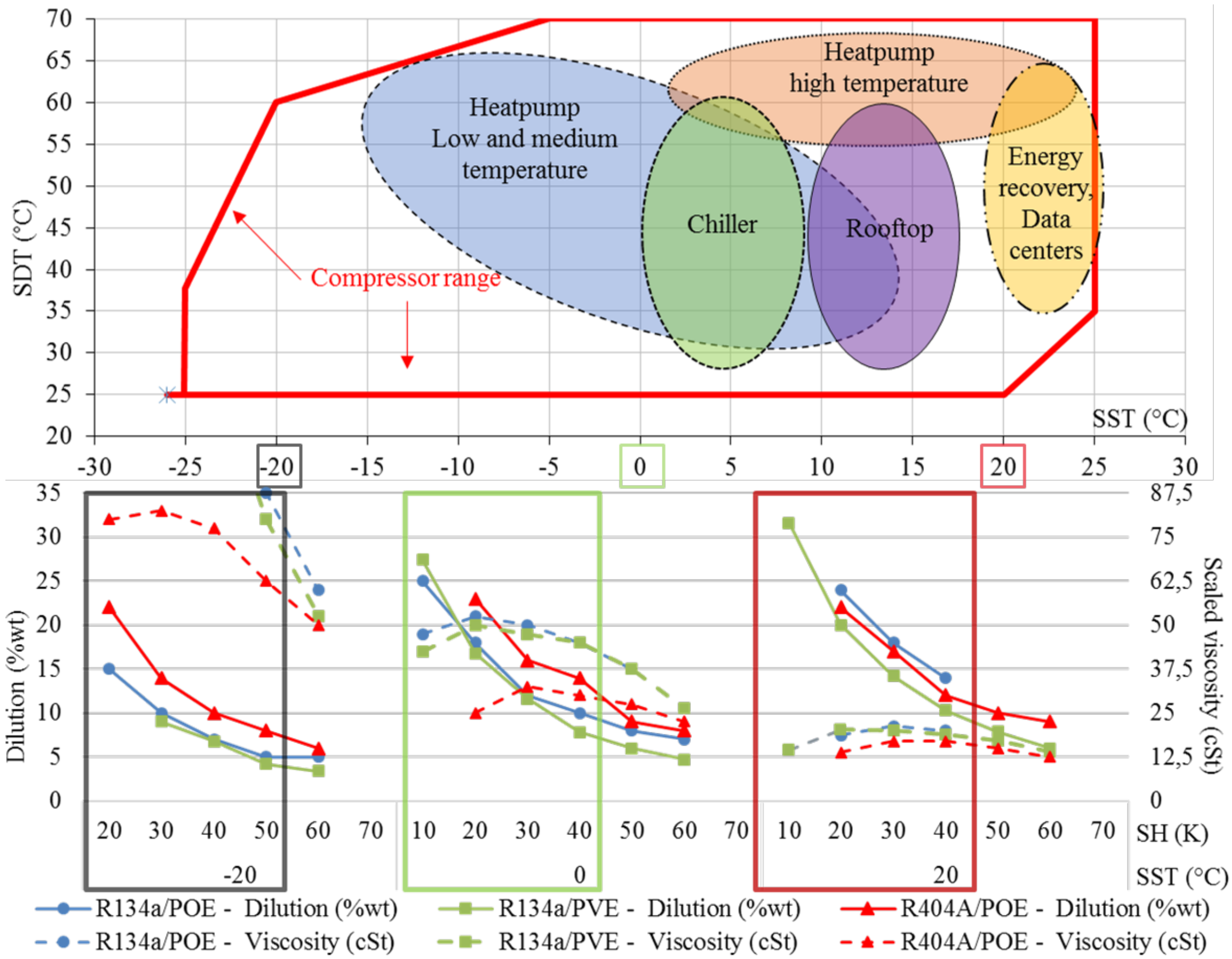

Figure 1: Compressor application and the corresponding sump conditions

2. MODELS FOR SOLUBILITY CALCULATION

The relative permittivity, also called dielectric constant, of a medium can be measured using a capacitor. The capacitance value of a capacitor depends on its geometry, on the vacuum permittivity and on the relative permittivity of the medium between the electrodes. The ratio of the capacitance C_0 in a vacuum and the capacitance C in the medium gives the relative permittivity of the medium as shown in Equation (1).

$$\frac{C}{C_0} = \frac{\varepsilon_{medium} * \varepsilon_0 * A}{\varepsilon_0 * A} = \varepsilon_{medium} \qquad (1)$$

Where A is a value depending on the geometry of the capacitance.

2.1 Mixing models

The medium is a mixture of lubricant and refrigerant. A mathematical model is required to link the mixture ratio with the capacitor value change. Four models linking the relative permittivity ε of a mixture to the proportions of its components were first considered (Table 1). These models consider two species where α is the volume fraction of the species 1.

The mass fraction is linked to the volume fraction by the following relation:

$$\varphi = \frac{1}{1 + \frac{\rho_{lub}}{\rho_{ref}} * (\alpha - 1)} \tag{2}$$

Table 1: Models linking relative permittivity to proportions

Linear (Böttcher, 1945)	C.R.I.M (Kraszewski, 1977)	Inverse	Rayleigh (1892)
$\varepsilon = \alpha\varepsilon_1 + (1-\alpha)\varepsilon_2$	$\sqrt{\varepsilon} = \alpha\sqrt{\varepsilon_1} + (1-\alpha)\sqrt{\varepsilon_2}$	$\frac{1}{\varepsilon} = \frac{\alpha}{\varepsilon_1} + \frac{(1-\alpha)}{\varepsilon_2}$	$\varepsilon = \varepsilon_2 + \frac{\alpha(\varepsilon_1 - \varepsilon_2)\frac{3\varepsilon_2}{2\varepsilon_2 + \varepsilon_1}}{1 - \frac{\alpha(\varepsilon_1 - \varepsilon_2)}{2\varepsilon_2 + \varepsilon_1}}$

In order to choose between the different mathematical models, a test using a Danfoss compressor was performed with a standard permittivity sensor. For different compressor operating conditions, the relative permittivity was measured using the permittivity sensor and the mass fraction was evaluated by sampling. Results are shown below (Figure 2), which indicate that the linear approach appears to be the most accurate, as concluded by Sedrez and Barbosa (2015) for mixtures of refrigerant and lubricant.

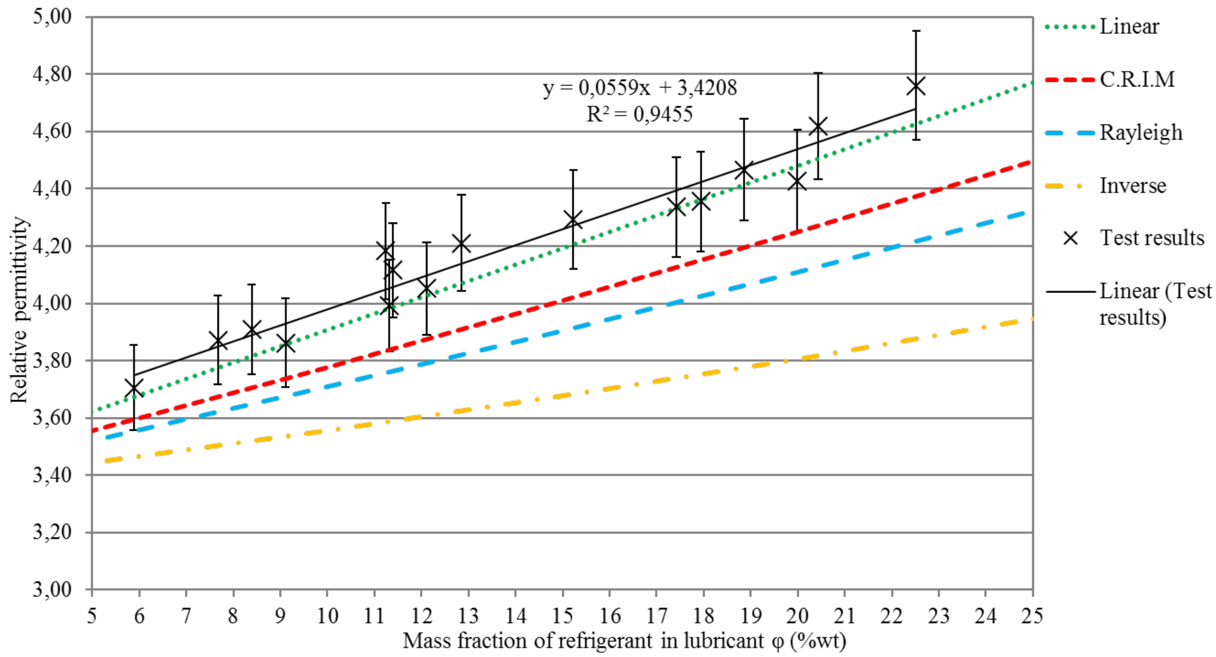

Figure 2: Relative permittivity of mixtures of R410A with a POE oil from theoretical models compared to test results

2.2 Pure fluids models

The relative permittivity of the pure refrigerant and the pure lubricant needs to be known in order to use the mixing model.

Several models of relative permittivity of pure liquid refrigerant for multiple refrigerants were identified. For R32, R125 and R134a, Abbott *et al.* (1999) proposed a model based on refrigerant temperature and density. The values of the coefficients A and B depend on the refrigerant used, ρ_r is the reduced density and the temperature is in Kelvin.

$$\frac{\varepsilon - 1}{2\varepsilon + 1} = A + B\rho_r \tag{3}$$

Another model, based on a state equation, was proposed for R152a (Barao *et al.* 1998), R143a (Gurova *et al.* 2009) and R410A (Brito et al., 2000), which also depends on temperature T and density ρ. The values of the coefficients c_0, c_1, d_0 and d_1 depend, once again, on the refrigerant used.

$$\varepsilon = c_0 + \frac{c_1}{T} + d_0\rho + d_1\frac{\rho}{T} \tag{4}$$

For R134a and R1234yf, Sedrez and Barbosa (2015) used a simpler model which depends only on the temperature (Equation 5).

$$\varepsilon = k_0 + \frac{k_1}{T} \tag{5}$$

The relative permittivity of a refrigerant, for which no model was found in the open literature, was estimated using a measurement from a standard permittivity sensor in the case of a pure species, for example for R1234ze. In the case of a mixture (R449A, R452A…), the relative permittivity was estimated using a linear mixing rule of it components without considering the interactions between the components.
This estimation method was used on R410A, for which a model was found (Brito et al. 2000), in order to evaluate the uncertainties introduced. Using the models for R32 and R125 from Abbott et al (1999), the relative permittivity of R410A was calculated and compared to the values from Brito et al. (2000). As shown in figure 3, the differences between the model and the mixing rule are important.

In the operating range of a compressor, it was found that these models could be simplified to linear ones (Equation 6). Here, b_1 and b_2 are coefficients which are dependent on the refrigerant and T is the temperature.

$$\varepsilon = b_0 + b_1 T \tag{6}$$

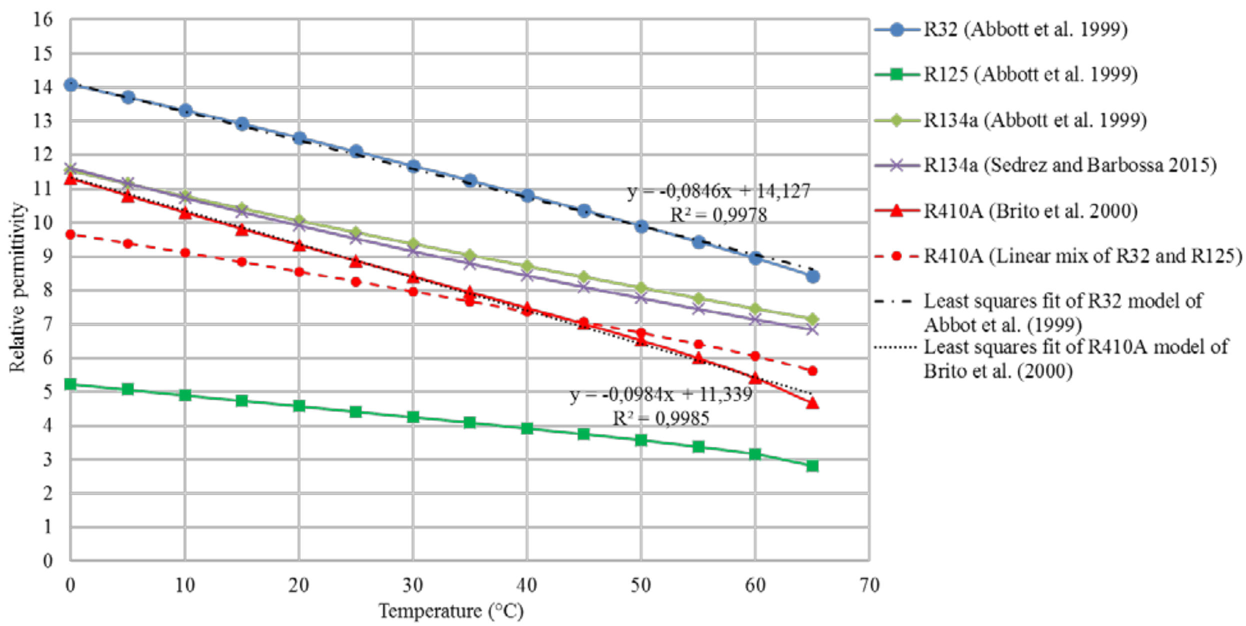

Figure 3: Relative permittivity of different refrigerants as a function of temperature

3. EXPERIMENTAL SET UP

3.1 Coaxial capacitors experiments

A capacitor was built to measure refrigerant relative permittivity. It is a closed cell made of copper tubes which allow measurement under pressure. This is typical for refrigerant measurements (Figure 4).

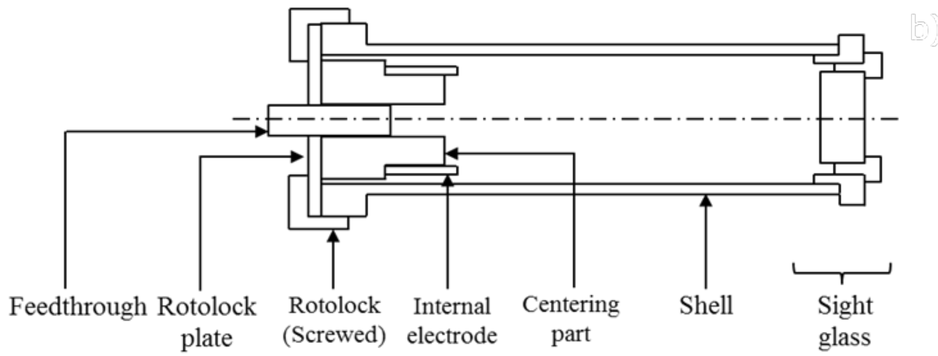

Figure 4: Simplified schematics of the first measuring cell

In this cell, the internal electrode is made by a copper tube of external diameter 1.125 inch (28.575 mm) and the external electrode, also made of copper, was the shell of the cell of external diameter 1.375 inch (34.925 mm). Both tubes had a 1 mm thickness. The external tube was closed by a screwed sight glass at one end and by a Rotolock fitting at the other. The Rotolock plate was equipped with a four pins feedthrough. One pin of the feedthrough was connected by a wire to the internal electrode. The external tube was also fitted with a service valve to allow for refrigerant charging. The internal electrode was fitted on a nylon PA6 centering part which itself was centered on the feedthrough.

During the filling of the cell with refrigerant, the sight glass was used to check the refrigerant level in order to achieve the correct charge and avoid the risk of too high a pressure. The liquid refrigerant needs to fill the space between the electrode to measure its relative permittivity. Therefore, the cell is held vertically with the electrodes at the bottom so the liquid refrigerant falls between the electrodes by gravity.

After each measurement, the cell was put under vacuum to remove the refrigerant. The gaskets of the fittings were subsequently changed and the capacitance in air was checked. The capacitor was then, once again, put under vacuum and the capacitance in vacuum was checked as well, before putting the next refrigerant charge in. This process was followed to avoid pollution of the sample by the previous ones and to comply to safety standards as some refrigerant used were flammable.

A measurement with the commonly used POE oil was performed as well using this cell. After this measurement, the cell was disassembled to clean the lubricant from the parts with a cloth and an alcohol to avoid polluting the following measurements.

The capacitance of the cell was measured using two different apparatus which were connected to the shell and to the pin connected to the internal electrode. The first apparatus was operated by charging and discharging the cell capacitor at 800Hz and using it to evaluate the cell capacitance by analyzing capacitor discharge time. The second apparatus is a LCR meter, which evaluates the capacitance of the cell by a bridge. The LCR meter measures frequencies of 0.1 kHz, 10 kHz and 100 kHz.

3.2 Measurement in compressor

Another series of measurements was performed in a compressor sump. A standard capacitive sensor was used which measures at a frequency of 16 kHz. The sensor was fitted on the lower part of the compressor shell, in a way that the measuring body was always immerged in the lubricant. The electronic part of the sensor was outside the shell. The sensor was connected to a computer equipped with the corresponding software, allowing data acquisition every second. The capacitance in picofarad and the temperature in degree Celsius were measured and the relative permittivity was computed by the sensor itself. The compressor was also fitted in the same manner with a viscometer, measuring every minute the viscosity in centipoise and the temperature in degree Celsius.

The compressor was then mounted on a test stand, simulating a system with an evaporator, a condenser and an expansion valve. Several conditions of saturated evaporating temperature, suction superheat and saturated condensing temperature were set. Conditions were changed only after stabilization. Several combinations of refrigerants and lubricants were studied.

Before filling the installation with refrigerant, the compressor, with its lubricant, and the test stand were put under vacuum for several hours to ensure that no air is present in the system. This is especially important when working with flammable refrigerants. During this pulling down under vacuum, the pure oil properties were measured. For dilution computations, the models presented previously are used. Additionally, the relative permittivity of the oil was considered constant and equal to the one measured while pulling down under vacuum the installation. The density of liquid refrigerant used for calculations was evaluated using the sump temperature and the evaporating pressure.

Additionally, sampling was performed at the highest evaporating temperatures and superheat to allow dilution ratio comparison with sampling method and data coming from the permittivity sensor.

4. RESULTS

4.1 Coaxial capacitors results

The measurements with the apparatus showed high relative permittivity values, above 10^3 in many cases as shown on Figure 5.

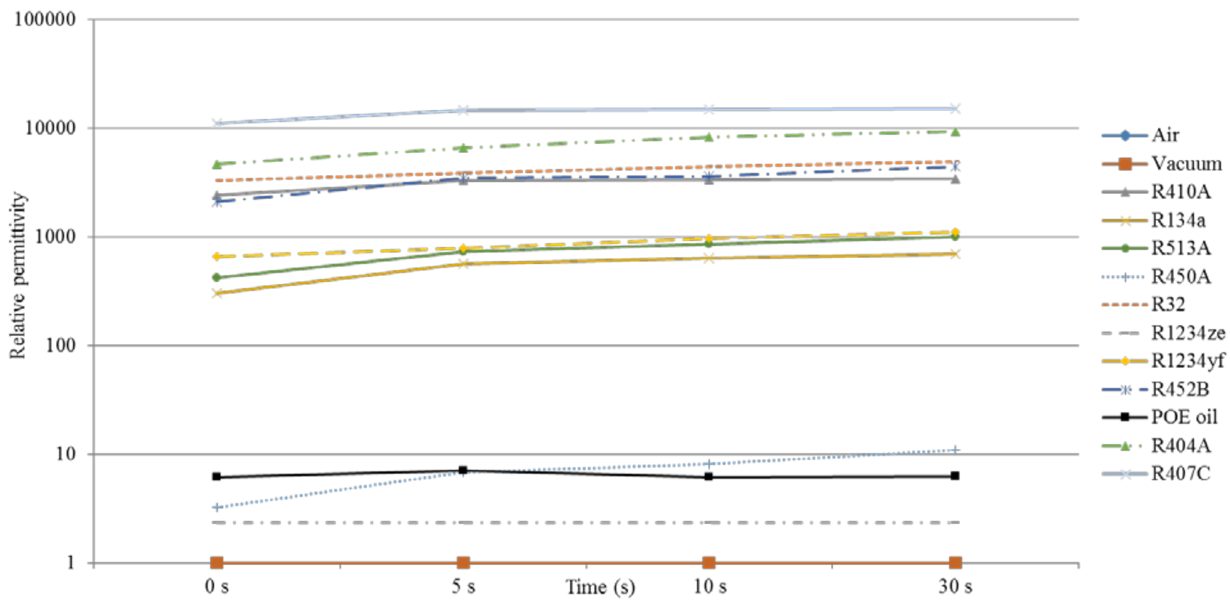

Figure 5: Relative permittivity measured with the cell and the first apparatus, function of time

The measurements with the LCR meter also showed high relative permittivity at 0.1kHz, up to 1000 for R32. At 10kHz and 100kHz, the measured relative permittivity was below 13 for all refrigerants (Figure 6).

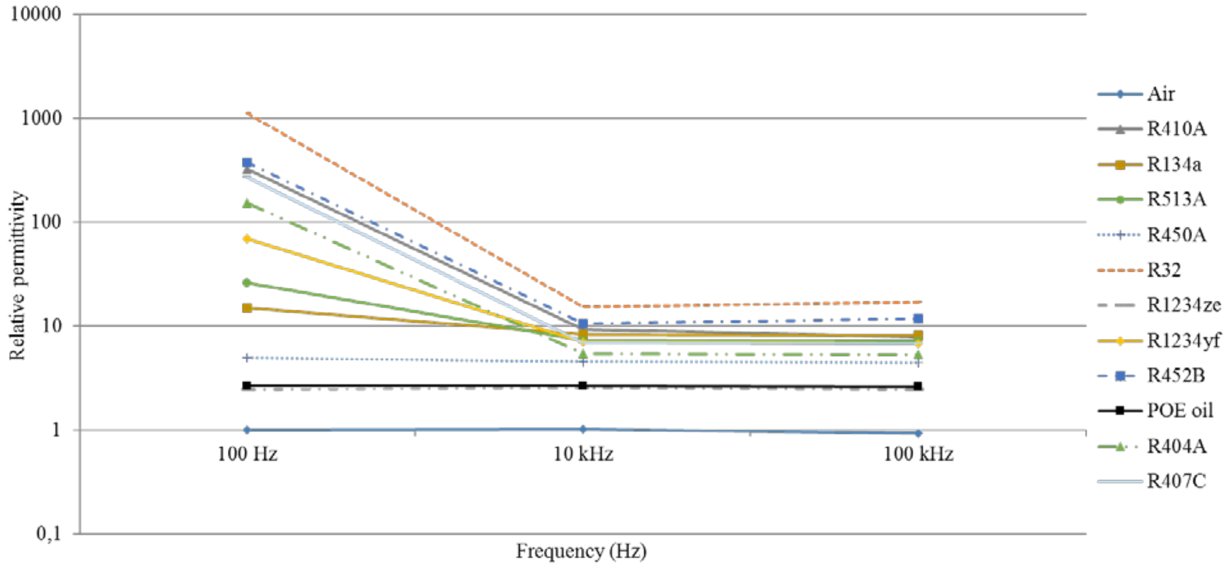

Figure 6: Relative permittivity measured using the cell and the LCR meter at multiple frequency

4.2 Measurement results in compressor

Measurements performed on two combinations of refrigerant and lubricant are presented below (Figure 7). As expected, the dilution of the refrigerant in the lubricant increases when the Saturated Suction Temperature (SST) increases. Also expected, the dilution decreases when the superheat increases. The temperature of the sump is higher with R32 than with R410A and this difference decreases when the SST increases.

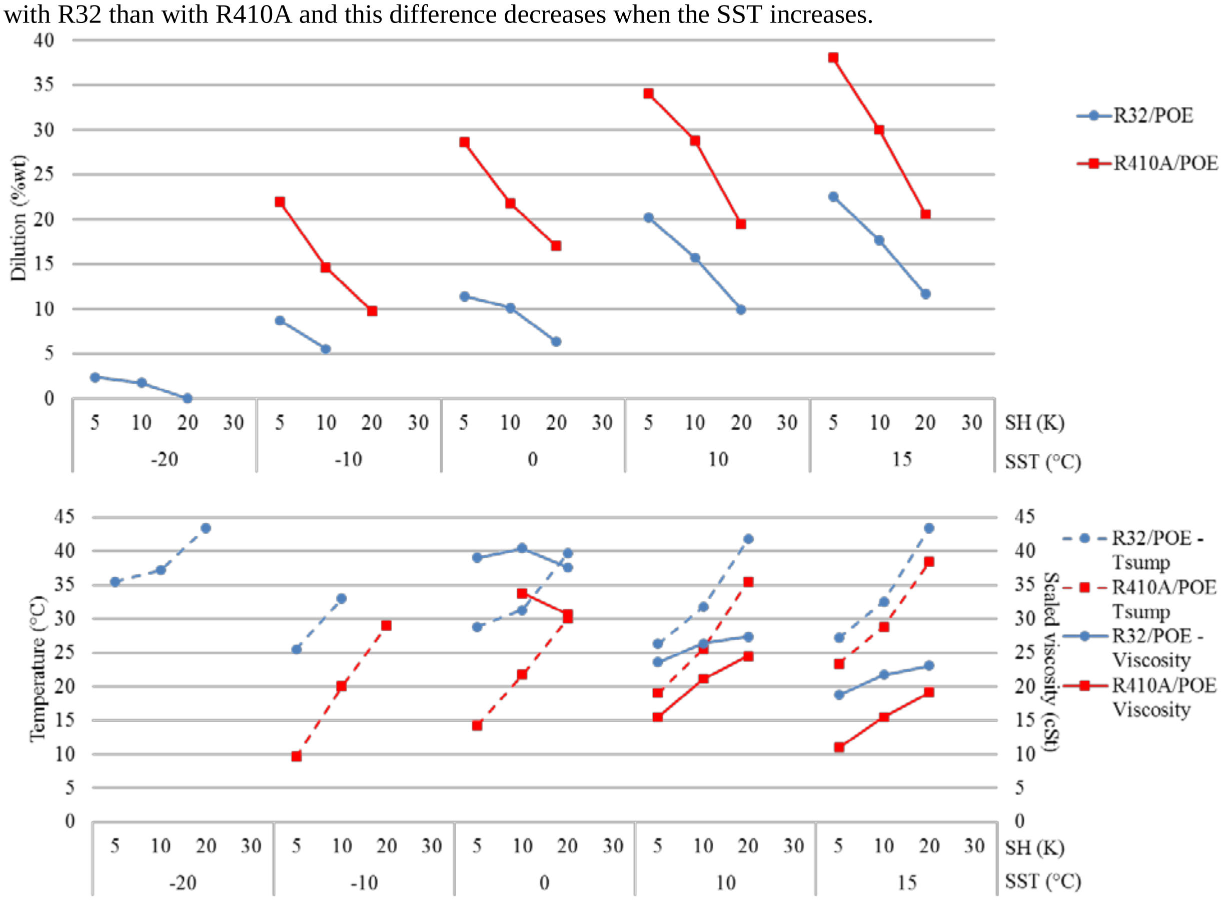

Figure 7: Dilution and viscosity of R410A and R32 in POE lubricant

5. DISCUSSION

5.1 Coaxial capacitors

The results from the first apparatus, operating by charging and discharging the capacitor, show a polarizing behavior for the refrigerants tested. The orientation of the molecules change to match the orientation of the electric field between the electrodes (Oh *et al.* 2007). This reorientation is also seen with the LCR meter at low frequency.

At higher frequency, the permittivity values measured with the LCR meter are close to the values found in the literature. Additionally, when compared to the models, the values obtained at 10kHz appear to be more accurate than those at 100kHz (Figure 8).

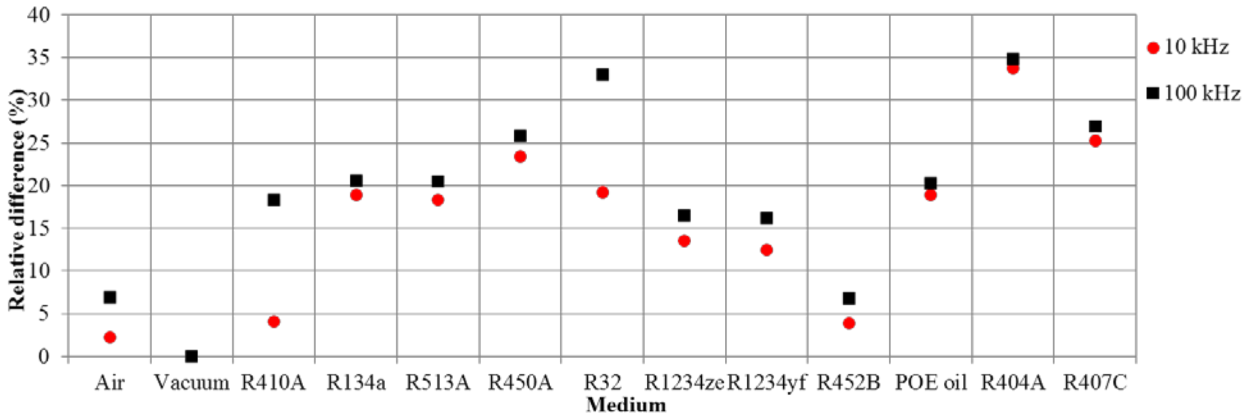

Figure 8: Results obtained from the LCR meter compared to theoretical values

5.2 Measurement in compressor

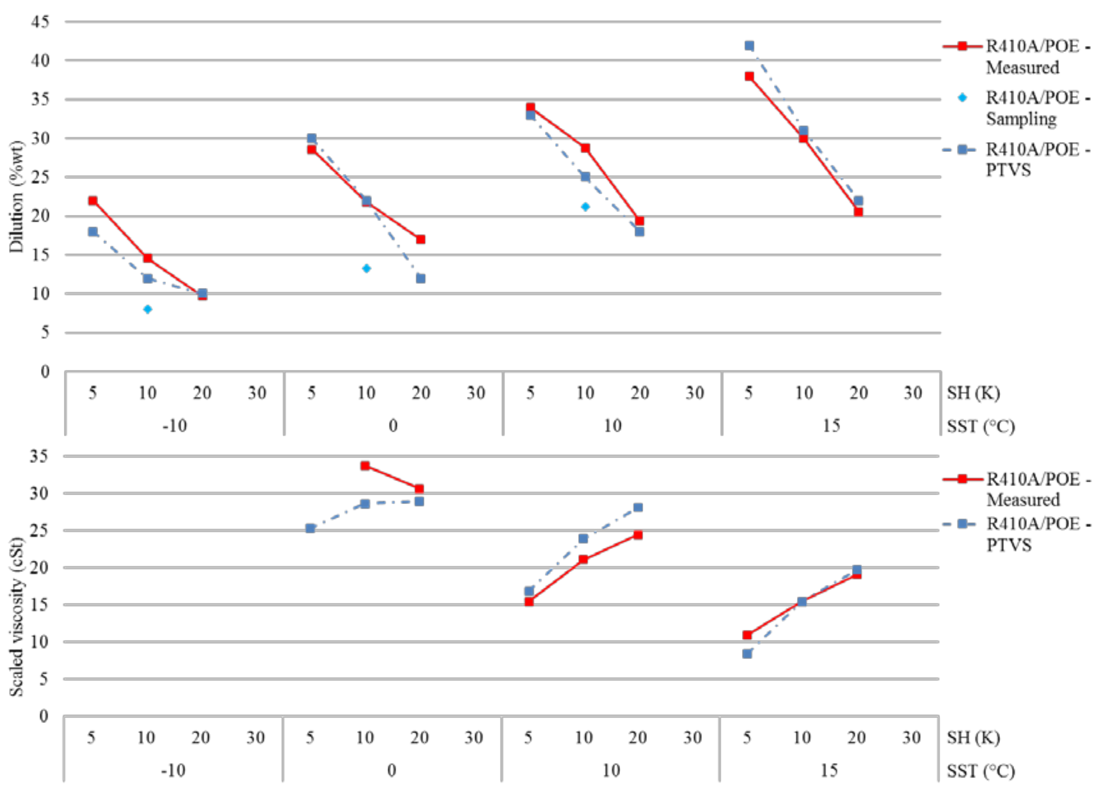

Figure 9: Comparison of measured dilution and measured viscosity to PTVS data

The results obtained are compared to PTVS data (Figure 8). Results obtained with the relative permittivity sensor are in good agreement with the PTVS data. The differences can be explained by measurement uncertainties, sump steering and also by uncertainties on the PTVS readings as data are interpolated. Additional uncertainties can be explained by the assumption of the negligible impact of the temperature on the lubricant relative permittivity and density

6. CONCLUSION

Measurements with the cell made of coaxial electrodes showed that the refrigerants have very high relative permittivity when measuring with a low frequency, highlighting a polarizing behavior of some refrigerants. At high frequency, above 10kHz, this behaviour disappears and the results are close to the values measured in previous studies.

The results obtained from the method presented in this paper are in good agreement with supplier's data. Therefore, when PTVS curve are not available, it is possible to obtain a part of it using this measuring method. This method can also be used, for example, in a laboratory environment to adjust a dilution level in a compressor for reliability testing.

The measurement method can also measure the oil sump lubricant - refrigerant mixture ratio without using the sampling method. This reduces the potential risk when flammable refrigerants are used and it is also more time efficient than sampling. In the same manner, the monitoring of the oil sump mixture composition is possible with this method under both steady state and transient conditions.

Monitoring under transient conditions represents a new step in controlling refrigerant dilution in the oil sump.

NOMENCLATURE

ε_0	Vacuum permittivity $\approx 8.854.10^{-12}$ F.m^{-1} (A^2.s^4.kg^{-1}.m^{-3})
ε_x	Relative permittivity of species x
ρ_x	Density (kg.m^{-3}) of species x
HC	Hydrocarbons
HFC	Hydrofluorocarbons
HFO	Hydrofluoroolefins
LGWP	Low Global Warming Potential
PTVS	Pressure Temperature Viscosity Solubility
POE	Polyolester oil
SH	Superheat (K)
SST	Saturated Suction Temperature (°C)

Subscripts

Ref	Refrigerant
Lub	Lubricant
Medium	Measured medium

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