

DIELECTRIC CONSTANT OF A NEAR-AZEOTROPIC HFC BLEND (R410A) IN LIQUID AND GAS PHASE

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Abstract. *The dielectric constant or relative permittivity of an environmentally acceptable near-azeotropic HFC blend (R410a) was evaluated experimentally. The temperatures and pressures span from 279 to 323 K and from 1 to 22 MPa to cover the liquid and gaseous states. A pressure-tight concentric cylinder cell was designed and manufactured according to the recommended criteria and standards. The gas and liquid capacitance measurement was performed by a commercial LCR bridge meter. The electrical connections were made according to the recommendations of LCR manufacturer. Two well-known substances were tested to calibrate the cell and validate the experimental procedure. The results of the dielectric constant measurement of R410a liquid phase were consistent with the results present in literature. The liquid phase dielectric constant decreases with increasing temperature and is 30% higher at the lowest tested temperature than at the highest. The dielectric constant for the gas phase remains almost constant and it is at least 7.6 times lower than for the liquid phase. The results show that it is possible to identify the R410a liquid and gas phases using their electrical properties, which it is very useful in many two-phase flow studies such as flow pattern recognition.*

Keywords: *dielectric properties, relative permittivity, dielectric measurements, R410a refrigerant*

1. INTRODUCTION

The measurement of electrical properties of refrigerants has been studied along the years by many authors, especially after the replacement of harmful refrigerants used in the traditional refrigeration systems by compounds which can be considered environmentally acceptable substitutes. These studies are targeted to miniaturization and development of high efficient compressors (Gbur, 2005), due to the increasing semi-hermetic and hermetic compressor use in refrigeration systems (Feja, 2012; Meurer et al., 2001), especially when there is direct contact between the refrigerant and compressor's electrically live parts. Other important scenario concerns to the electrical behavior of oil-refrigerant mixtures used in hermetic compressors (Sedrez and Barbosa, 2015) and in the design of capacitive or resistive sensor capable of fraction phase detection in two-phase flows studies (Rosa et al., 2012). An extensive literature review of the liquid phase electric properties measurements for refrigerants, pure compounds or blends, with temperature ranging from 202 to 303 K and pressure from 0.10 to 18 MPa was presented by Ribeiro and Nieto de Castro (2011). For the gas phase, the authors only presented data for R-134a, with temperature ranging from 298 to 323 K and pressure from 0.12 to 1.25 MPa

The R410a is becoming the standard refrigerant in new residential and light commercial air conditioning equipment (Brito et al., 2000), despite being a nearly azeotropic mixture (50/50% in mass mixture of R32 and R125). Such replacement leads to improved compressor efficiency and reduced energy consumption in the other components (Brito et al., 2000). Other important characteristic of R410a is relatively low critical temperature and pressure (346K and 5 MPa), which allow its use in two-phase flow studies when the gas and the liquid have the same density. There are only a few studies in this field, many of them using sulphurhexafluorid (SF6) and water. The electrical nonconductiveness of the SF6 allows it to be used in two-phase studies using impedance sensors to measure the phase fraction as proposed by Rosa et al. (2012).

Electrical proprieties of fluids have been used to obtain two-phase flow parameters because of its simple measure principle that uses an easy construction sensor. Resistance, capacitive or impedance measurements have some advantages and some disadvantages. According to Maxwell's theory, the permittivity or resistivity of a mixture is related to the volumetric concentration and the properties of each phase of the mixture. To properly design a sensor to operate with a particular mixture, it is very important to have advanced knowledge of the electrical properties of each component. Therefore, in order to use R410a at saturation in gas liquid two-phase flow studies using electrical property measuring sensors, it is necessary to know the electrical properties of each phase.

Refrigerant electrical properties literature reviews have shown that most work has been done with the liquid phase only. There has been only one study reported about the gas phase cited above. For R410a, Brito et al. (2000) presents the electrical properties with temperature and pressure ranging from 217 to 304 K and 2 to 16 MPa, respectively. So, in all tested cases the R410a was a subcooled liquid. Thus, the main objective of this paper is to measure the electrical properties

of gas phase R410a to be used in impedance sensor design capable of detecting the phase present in a gas liquid two-phase flow with saturated R410a. A specific objective of this work is the design and manufacture of a high pressure capacitive cell capable of electrical properties measurement, its calibration procedure and its test with known substances.

2. EXPERIMENTAL METHODOLOGY

A high pressure capacitive cell with a homogeneous electrical field, measurable parasitic impedances and a system that allows thermodynamics equilibrium of the refrigerant inside the cell at different temperatures is necessary for the measurement of the electrical properties of refrigerants. In this paper a capacitive cell was designed and manufactured taking into account the literature recommendation (ASTM D1169-11, 2011; ASTM-D-924, 2008; Feja, 2012). Figures 1.(a) and (b) show a photographic image and a sketch with the main cell dimensions, respectively. A Teledyne Isco syringe pump model 260 D was used to fill the capacitive cell with subcooled liquid in a constant pressure process. The pump's maximum operational pressure and temperature were 50 MPa and 313 K, respectively. The pressure gauge has accuracy of 0.25 MPa. The fulfilled cell was stowed into a customize Marcone climate chamber model MA1415/300/E. The operational temperature spun from 273 to 333 K with +/- 0.5 K accuracy and uniformity of 1 K. A BK Precisión LCR bridge model 889A was used to measure the refrigerant capacitance between the two cell electrodes. The LRC bridge is capable of measuring capacitance from 0.003 pF to 80.00 mF with voltage and frequency ranging from 0.05 to 1 V and from 0.1 to 200 kHz with less than 2% accuracy.



Figure 1. (a.1) inner and outer electrode (a.2) outside and inside (a.3); (b) a schematic diagram of the assembled measurement cell.

2.1 Calibration

The relative permittivity (ϵ_x) of an unknown substance inside a cell without a protection ring can be calculated according to Feja (2012) by:

$$\epsilon_x = \frac{C_x - C_g}{C_e}, \quad (1)$$

where C_x , C_e and C_g are the capacity of the fulfilled cell with the unknown substance, the parasitic and the geometrical cell itself respectively. C_e and C_g are related to the capacity measurement system (LCR bridge setup, cables, electrical contacts, etc) and the capacitance due to geometrical cell characteristics and should be determined for a cell without a protection ring. It is possible to determine the parasitic's and cell's geometric capacitance testing two well-known substances using:

$$C_g = \frac{C_2 \epsilon_1 - C_1 \epsilon_2}{\epsilon_1 - \epsilon_2}, \quad (2)$$

$$C_e = \frac{C_1 - C_2}{\varepsilon_1 - \varepsilon_2}, \quad (3)$$

where ε and C are the relative permittivity and the measured cell capacitance fulfilled with the well-known substances. The parasitic and geometrical capacitances don't depend on the tested well-known substances and should not be a function of the temperature parameter. In this work, dry air and liquid CO₂ were the well-known substances used. The dry air relative permittivity measured by Hector and Schultz (1936) is $\varepsilon = 1.00058986 \pm 0.00000050$ and it is constant with temperature. Moriyoshi et al. (1993) measured the CO₂'s relative permittivity for several temperatures and pressures with 0.02% accuracy. The pressure and temperature tested in this work were not coincident with data from Moriyoshi et al. (1993) and a correction procedure had to be performed. Brito et al. (2000) shows that the relative permittivity can be fitted as a function of density (ρ in kg.m⁻³) and temperature (T in K) as bellow:

$$\varepsilon(T, \rho) = A_0 + A_1/T + A_2\rho + A_3\rho/T, \quad (4)$$

where A's are fitted coefficients. In this work, the density was calculated using the Multiflash 6.014 software with a cubic plus association Infochem state equation (EOS CPA-Infochem) from the tested temperature and pressure and the A's coefficients were fitted using minimum mean square. The relative permittivity maximum deviation using the fitting proposed by Eq. (4) with the coefficients shown in Table 1 and the Moriyoshi's experimental data was less than 3%.

Table 1 – Coefficients of Eq. (4) for liquid density

| Substance | A ₀ | A ₁ [K] | A ₂ [m3/kg] | A ₃ [K.m3/kg] |
|-----------------|----------------|--------------------|------------------------|--------------------------|
| CO ₂ | 0.54714 | 166.1005 | 0.001071 | -0.16204 |
| R410a | 12.01200 | -5159.000 | -0.010188 | 7.02700 |

The experimental procedure to measure the capacitance with calibration substances was similar. First of all, the cell was careful cleaned to remove any previous residue. For dry air, the cell was stowed in climate chamber at 323 K for three hours to reach the thermodynamic equilibrium with the temperature measured in the climate chamber. After three hours, the cell was closed and the test begun. The capacitance was measured with temperature ranging from 278 to 323 K, increasing and decreasing the temperature in 5 K intervals with at least three repetitions for each temperature. The three hours waiting period was repeated for each temperature to establish a homogenous temperature distribution all over the climate chamber and for the thermodynamics equilibrium to be reached. For CO₂ the cell was fulfilled with liquid CO₂ at 9.6 MPa and 293 K using the Teledyne syring pump. The cell was stowed in the climate chamber and the same conditions as the dry air capacitance measurements were applied. The measured capacitance for dry air and CO₂ is shown in Table 2 as well as the C_e and C_g constants values. The C_e and C_g constants as a function of temperature is shown in Figure 2 and the constants have the expected temperature independency. An error propagation analysis was done considering the bias and precision limits for all variables and measured instruments with 95% confidence interval and the cell's calibration constants and their uncertainties are: C_e = 14.68 ± 1.13 pF e C_g = 147.91 ± 1.42 pF.

Table 2 – Dry air and liquid CO₂ measured capacitance and cell calibration constants.

| T [K] | C _{co2} [pF] | ε_{co2} | C _{air} [pF] | ε_{air} | C _e [pF] | C _g [pF] |
|--------|-----------------------|---------------------|-----------------------|---------------------|---------------------|---------------------|
| 279.55 | 170.26 | 1.536099 | 161.67 | 1.00059 | 16.04 | 145.62 |
| 283.15 | 170.21 | 1.519654 | 162.87 | 1.00059 | 14.14 | 148.72 |
| 288.15 | 170.89 | 1.517234 | 163.13 | 1.00059 | 15.00 | 148.12 |
| 293.15 | 170.36 | 1.514898 | 162.77 | 1.00059 | 14.75 | 148.00 |
| 298.15 | 169.87 | 1.512639 | 161.93 | 1.00059 | 15.50 | 146.42 |
| 303.15 | 170.06 | 1.510455 | 162.30 | 1.00059 | 15.21 | 147.08 |
| 308.15 | 169.97 | 1.508342 | 162.50 | 1.00059 | 14.71 | 147.78 |
| 313.15 | 169.71 | 1.506296 | 162.87 | 1.00059 | 13.52 | 149.34 |
| 318.15 | 169.51 | 1.504315 | 163.07 | 1.00059 | 12.78 | 150.28 |
| 323.15 | 170.52 | 1.502395 | 162.90 | 1.00059 | 15.19 | 147.71 |

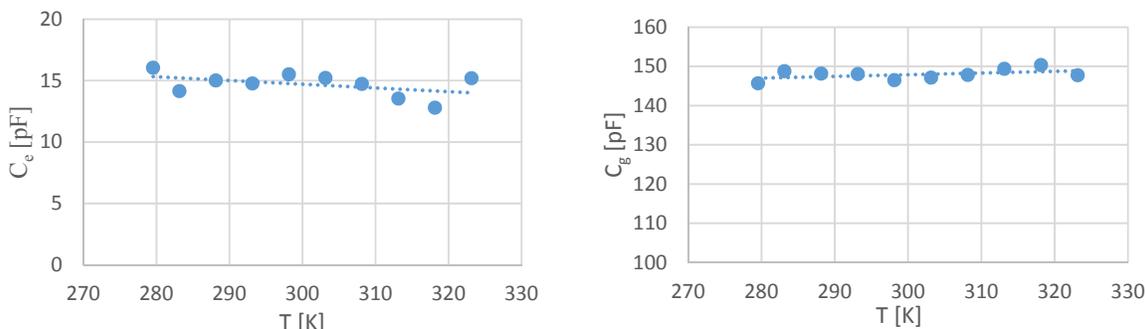


Figure 2. Cell calibrations constants as function of temperature.

2.2 R410a Measurement

After the cell's calibration procedure was done, the R410a capacitance measurement in liquid and gas phases could be done. The procedure for the liquid R410a was similar to CO₂ process and the tested R410a was supplied by Dupont¹ in drum tanks with 11.35 kg. The liquid phase was pumped out of the tank using the Teledyne syringe pump until the cell was fulfilled with liquid R410a at 6.14 MPa and 293 K. Table 3 shows the tested R410a main thermophysical properties. Before and after the cell was fulfilled, the cell weight was measured using a Shimadzu UX8200S balance with 0.1 g minimum display and accuracy class II. Afterwards, the cell was stowed in climate chamber and the capacitances were measured with temperatures ranging from 279 to 323 K with 2 K intervals. A three hours waiting period was taken for a complete temperature homogenization and thermodynamic equilibrium. For the gas phase capacitance measurement, the R410a inside the cell was drained to assure that there was only gas in contact with the cell's electrodes. The mass requiring removal was calculated by an expansion process at constant temperature. Only after the cell was fulfilled with a gas only phase, it was stowed in the climate chamber at 323 K and the capacitance was measured to 279 K with 2 K intervals, with a three hours waiting period for each temperature. All capacitance measurements (liquid and gas) were performed 3 times, both with increasing and decreasing temperature changes. The uncertainty for the liquid and gas capacitance with 95% confidence interval was calculated in 6.99 and 0.37 pF, respectively.

Table 3 – R410a properties

| Chemical Formula | Molecular Weight | Boiling point at 101.3kPa | Critical properties | | | |
|--|------------------|---------------------------|---------------------|----------------------|-----------------------------|------------------------------|
| | | | Temperature [K] | Pressure [MPa – abs] | Volume [m ³ /kg] | Density [kg/m ³] |
| CH ₂ F ₂ /CHF ₂ CF ₃ 50/50% by weight | 72.58 | -221.30 K | 345 | 4.9261 | 0.00205 | 488.90 |

3. RESULTS

Figure 3 shows a comparative study between the measured relative permittivity and the experimental data for R410a in liquid phase from Brito et al. (2000). It also shows dotted lines for the $\pm 10\%$ limits. The data shown for all relative permittivity measured in this work coincide with Brito's data for all tested cases, with two points out of $\pm 10\%$ limits. The data from Brito et al. (2000) was adapted for this work's measuring conditions for temperature and pressure using Eq. (4) and the coefficients are shown in Table 1. The Multiflash software with a EOS CPA-Infochem was used to calculate density in this work. Brito et al. (2000) used the hard sphere deSantis model with the mixture and combination rule. The maximum deviation between the density presented by the authors and the one using Multiflash was 6% and between adjusted permittivity and the author's relative permittivity was 12%. The largest relative permittivity and density deviations were for the low pressures and high temperatures. In such conditions, the stated equations for the subcooled liquid presented the highest error and the two points out of bounds shown in Figure 3 reflect this condition. Therefore, it's impossible to ensure if the deviation is due to the measured relative permittivity or to the fitted data. In any case, the measuring procedure for relative permittivity can be considered acceptable for the purpose of this work, which is to measure the R410a relative difference between the gas and liquid phases permittivity.

¹ The commercial designation for Dupont R410a is SUVA 410a.

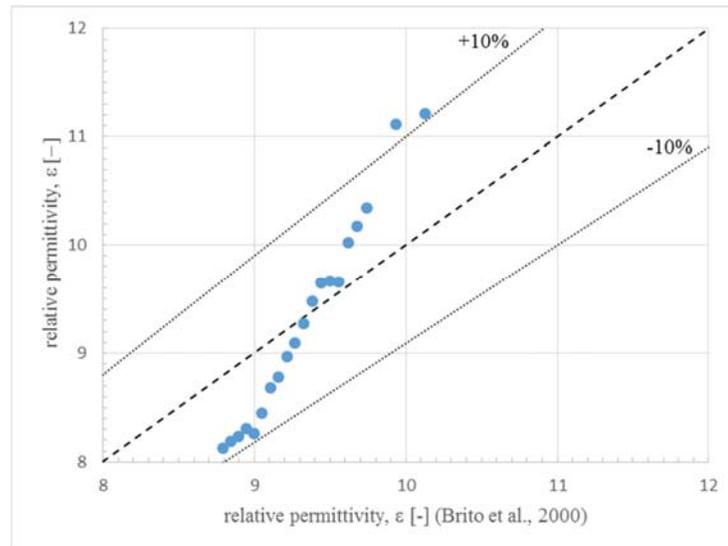


Figure 3. Comparison between the measured relative permittivity and Brito et al. (2000)

Figure 4 shows the relative permittivity as a function of temperature for R410a in liquid and gas phases. The temperature spans from 290 to 320 K, and the gas phase behavior shows temperature independency. The gas relative permittivity was constant around one, as expected for gases. The liquid phase relative permittivity diminished with temperature increase, spanning between 11 and 8 for the measured temperature range. The values are typical for non-conducting liquids, as expected also. The liquid and gas permittivity ratio has a minimum of 8. Therefore, in order to use saturated R410 mixture in two-phase flow studies a special electrical circuit development capable of distinguishing relative permittivity in this range is necessary.

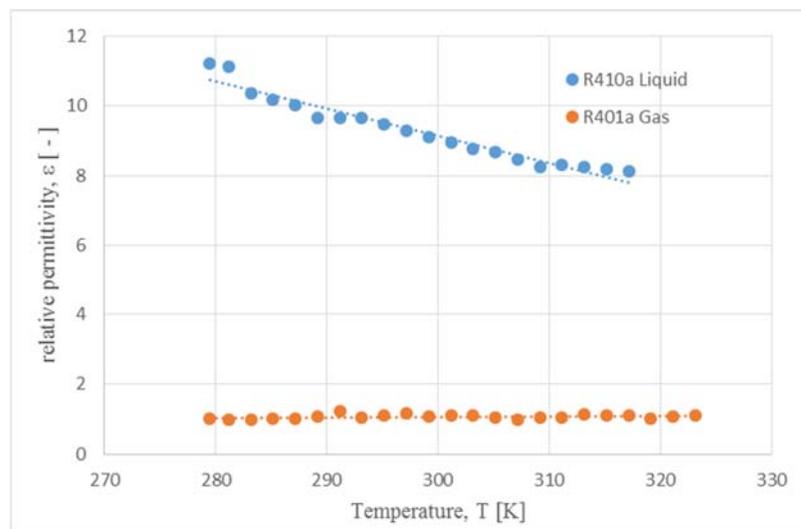


Figure 4 – Relative permittivity of R410a liquid and gas as functions of temperature.

4. CONCLUSIONS

A high pressure cell without protection ring was manufactured and used to measure the relative permittivity of the R410a in gas and liquid phases. The cell was calibrated using dry air and liquid CO₂ for temperatures ranging from 280 to 320 K. The obtained calibrations constants were temperature independent. A commercial R410a supply (Dupont SUVA 410a) was used for relative permittivity in gas and liquid phase. In both phases, the measurements were done with temperature ranging from 280 and 320K. The measured liquid R410a relative permittivity is in accordance to the values found in literature data ($11 \leq \epsilon \leq 8$) and was constant for the gas phase R410a ($\epsilon \approx 1$).

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