Experimental investigation of the variation of HFE electric properties with temperature

Michelle Nassar[1*], Christophe Louste[2], Anny Michel[3], Michel Daaboul[4]
[1,2,3] CNRS – University of Poitiers – ISAE-ENSMA – UPR 3346, France
[4] Mechanical Engineering Department, University of Balamand, Lebanon
*phone: +33 7 63 22 32 18
*e-mail: michelle.nassar@univ-poitiers.fr

***Abstract*—Dielectric properties of HFE-7100 are investigated in a temperature range between –20°C and 60°C. The aim is to electrically characterize this liquid due to its promising importance in the Electrohydrodynamics (EHD) field. Results show a linear decrease of relative permittivity with temperature rise. However, the dissipation factor, the conductivity and the resistivity manifest an unusual behavior. Increasing the temperature results in a decrease in both the dissipation factor and the conductivity and in an increase in resistivity. At 25°C, the calculated values of relative permittivity and electrical resistivity are 6.72 and 2.30×10^{10} Ω/cm, respectively. These values differ from the ones presented in the data sheets of HFE.**

I. INTRODUCTION

HFE-7100, also known as hydrofluoroether or methoxy-nonafluorobutane ($C_4F_9OCH_3$) is a dielectric fluid with interesting electrohydrodynamic (EHD) properties. This complex organic solvent has promising EHD applications, especially in the domain of heat transfer. It could be ideally utilized in EHD pumps for semiconductor and pharmaceutical industries, electronic cooling, refrigeration... [1] Being a transparent, nonflammable, nontoxic and low-odor dielectric fluid with environmentally friendly properties, it was first fabricated as a replacement for ozone-depleting substances and compounds with high global warming potential such as CFCs, HFCs, HCFCs, and PFCs [2].

Due to its importance in EHD, numerical simulations must be carried out in order to enhance the performance of EHD systems, especially in the presence of wide temperature variations. Unfortunately, the data sheets of HFE-7100 only provide little information on the variations of some of its physical properties with temperature [1].

This paper aims to study the influence of temperature on the dielectric properties of HFE-7100 (dielectric dissipation factor DF, relative permittivity ε_r, permittivity ε, electric conductivity σ, and resistivity ρ). This is done by experimental investigation of the capacity (C) and conductance (G) of a test cell at different temperatures (–20°C to 60°C). The equations that relate capacity and conductance to the above mentioned dielectric properties are the following:

$$DF = \tan\delta = G/100\pi C \qquad (1)$$

$$\varepsilon_r = C / C_0 \tag{2}$$

$$\sigma = \varepsilon G / C \tag{3}$$

$$\rho = 1/\sigma \tag{4}$$

Previous papers show that similar experiments were carried out to characterize the dielectric properties of other liquids such as MOL and NYNAS virgin oils [3], mixtures of mineral oil and methyl ester with different ester contents [4], and synthetic ester liquid (Midel 7131^{TM}) [5] over a large temperature range.

II. EXPERIMENTAL SET-UP AND WORKING LIQUID

A. Experimental Set-Up

A schematic view of the experimental apparatus is shown in Fig. 1. Measurements were conducted using a stainless steel test cell designed with two coaxial cylindrical electrodes with a gap of 3.5 mm. The cell's reservoir and electrodes support form a Faraday cage. This cell with very low losses (tan $\delta_0 < 5\times10^{-7}$ at 50 Hz) has an air capacitance $C_0 = 23.2$ pF. It is sealed so it can be immersed in a thermostatic bath, allowing temperature control between –20°C and 60°C. It has a pressure control sensor and is connected to an IRLAB model LDTR-4 analyzer for the characterization of insulating liquids. The analyzer satisfies the instructions of IEC 61620 [6]. It generates an alternating trapezoidal wave of 10 V that has a frequency of 0.5 Hz and a rise time between 1 and 100 ms. After measuring the charging and conduction currents of the cell, this device displays the cell's capacitance (C) and conductance (G) within a range of 10-2000 pF and 10^{-10}-10^{-16} S, respectively. It then calculates the dissipation factor at 50 Hz.

In order to avoid measurement bias associated with liquid aging, experiments were conducted in two phases. The first one was a descent in temperature from 60°C to –20°C. The second one was an ascent from –20°C back to 60°C with steps of 5°C. All measurements were recorded on a computer every 4 minutes.

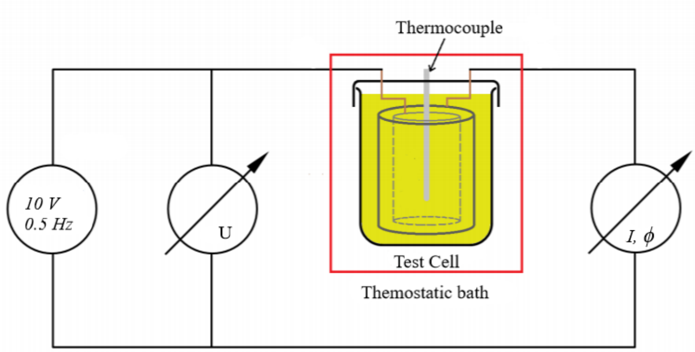

Fig. 1. Schematic view of the test cell used for the dielectric measurements.

B. Working Liquid

Based on the product and application information documents [1, 2], HFE-7100 has many useful dielectric applications because of its wide liquid range (–135°C to 61°C), its low surface tension, its low viscosity, and its compatibility with most metals, plastics and elastomers. Some of its important physical properties are given by the following formulas:

$$\text{Liquid density [kg/m}^3\text{]} = -2.2690\times T\ [^\circ\text{C}] + 1538.3 \quad (5)$$

$$\text{Thermal conductivity [W/m.K]} = -0.00019548\times T\ [^\circ\text{C}] + 0.073714 \quad (6)$$

$$\text{Liquid specific heat [J/kg.}^\circ\text{C]} = 2.00\times T\ [^\circ\text{C}] + 1133 \quad (7)$$

At 20°C room temperature, 303 g of the liquid were carefully poured in the test cell. This corresponds to a volume of 204 mL.

III. EXPERIMENTAL MEASUREMENTS

At each test temperature, the system is allowed sufficient time to stabilize and reach a steady-state. Fig. 2 and 3 present the temporal evolution of the capacitance and the conductance at 20°C, respectively. The data acquisition frequency is 1 sample per 240 seconds. Therefore, an acquisition time of about 1 day 20 hours is needed to record 660 samples. It can be seen in these figures that a steady state is reached after a few minutes. For precision reasons, the last 50 measurements at each temperature were considered in order to calculate the average m and the standard deviation of the dielectric properties. Using $m \pm \sqrt{\frac{\sum_1^N (x-m)^2}{N-1}}$, the error was found to be less than 0.3% for capacitance and less than 6% for conductance which makes the standard deviation not clearly visible on the graphs.

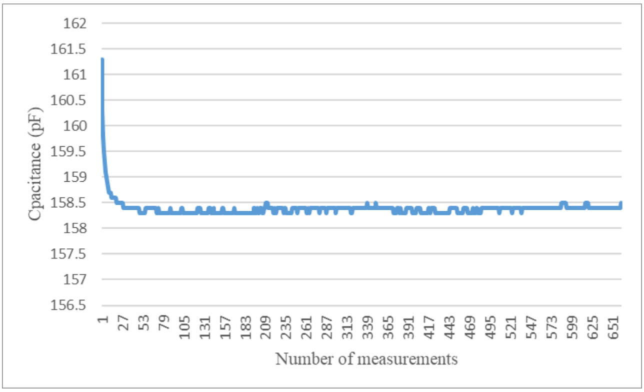

Fig. 2. The evolution of capacitance with time at 20°C.

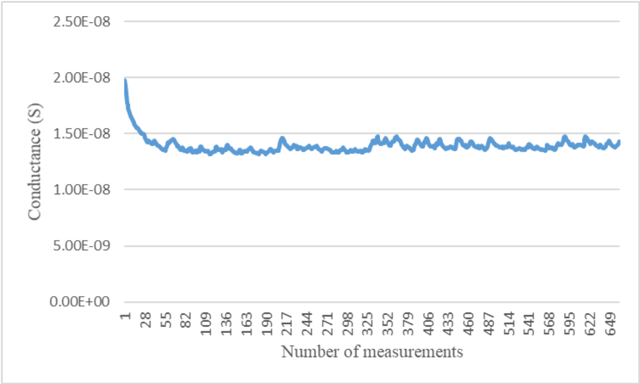

Fig. 3. The evolution of conductance with time at 20°C.

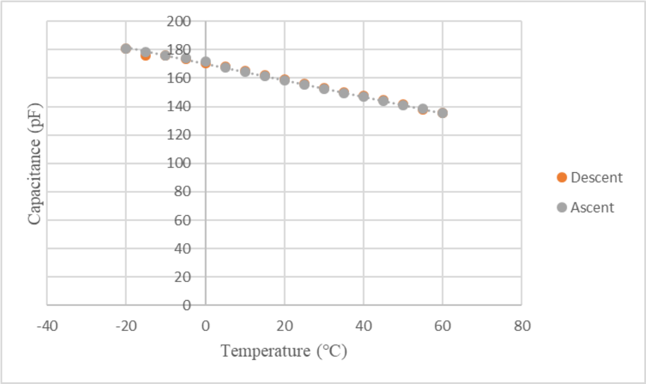

Fig. 4. Capacitance as a function of temperature.

The capacitance as a function of temperature, depicted in Fig. 4, shows a linear decrease when the temperature increases. Repeatability of results is proven by having fairly the same curves for both the descent and the ascent in temperature.

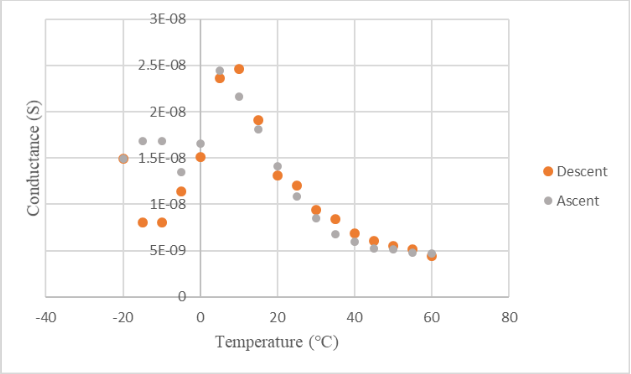

Fig. 5. Conductance as a function of temperature.

Fig. 5 shows that increasing the temperature from 5°C to 60°C leads to a 5 times variation in conductance. This behavior of conductance with temperature is very unusual compared to literature since conductance should increase with temperature rise [5]. Results are reasonably similar during the ascent and descent for this range of temperature. However, the conductance behavior becomes random for temperatures below 0°C. This point is discussed in the following section.

IV. ANALYSIS OF RESULTS AND DISCUSSION

A. Treatment of Data

The relative permittivity can be calculated using equation (2). Results are presented in Fig. 6.

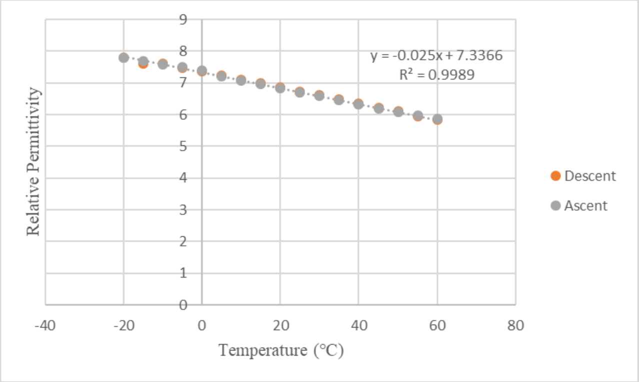

Fig. 6. Relative permittivity as a function of temperature.

It can be seen that, for temperatures going from –20°C to 60°C, the relative permittivity decreases linearly. The total decrease within this temperature range is around 33%. Such behavior has been described for other liquids in previous papers [5, 7, 8].

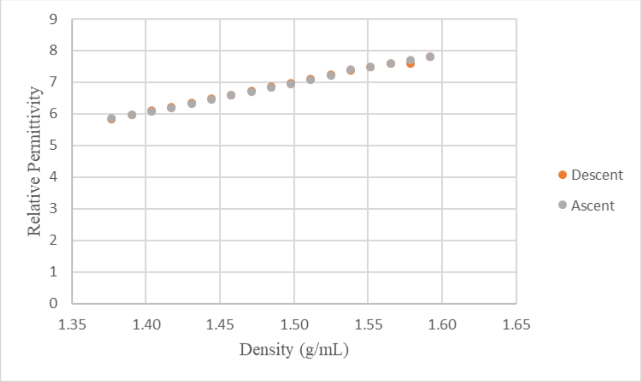

Fig. 7. Relative permittivity as a function of density.

This important decrease in permittivity with temperature is correlated to the decrease in HFE density, shown in Fig. 7, and a linear behavior is obtained. In fact, as HFE expands with increasing temperature, there are less dipole moments per unit volume.

Applying equations (1), (3) and (4) to calculate the other dielectric properties at different temperatures leads to the following graphs:

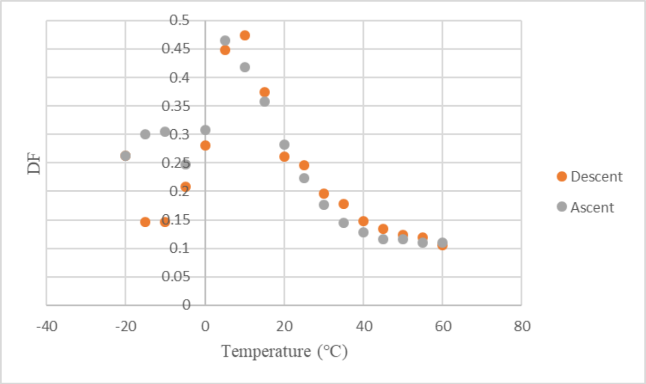

Fig. 8. DF as a function of temperature.

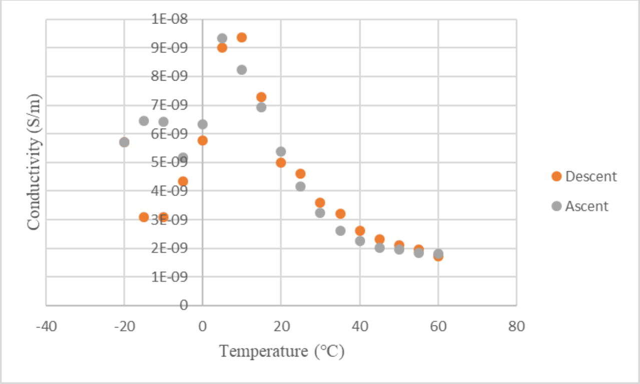

Fig. 9. Conductivity as a function of temperature.

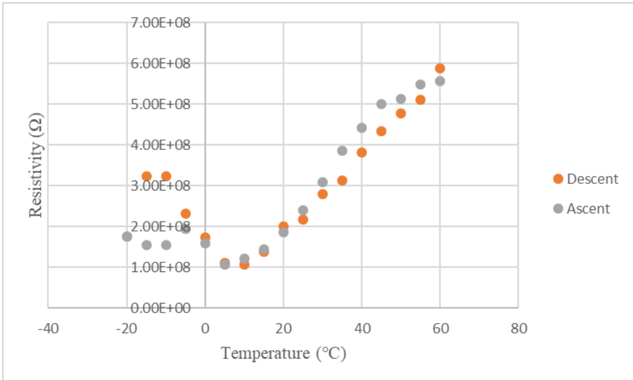

Fig. 10. Resistivity as a function of temperature.

Figs. 8, 9, and 10 present the variations of the dissipation factor, of the conductivity, and of the resistivity, respectively, as a function of temperature. It can be seen that a large hysteresis behavior is visible on DF and conductivity curves between –20°C and -10°C. In order to explain this behavior, the expansion and compression of HFE with temperature has to be analyzed. This phenomenon may be explained by considering the liquid density. The cell contains exactly 303 g of liquid and the critical height for which the electrodes are completely submerged in the liquid is experimentally shown to be 58.5 mm. Therefore, the liquid height at each temperature can be measured and compared to the critical height. Fig. 11 shows that the HFE height becomes less than the critical height for temperatures below 0°C. Hence, all measurements at these temperatures are unreliable.

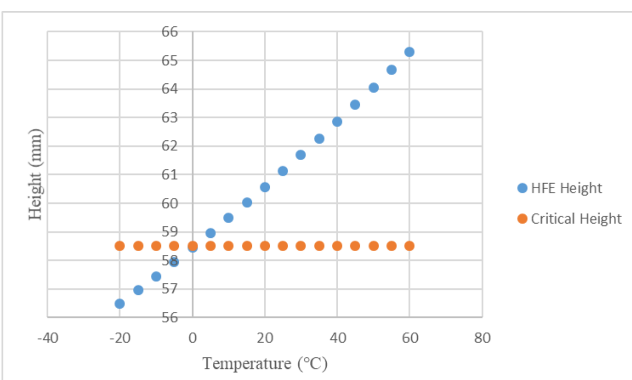

Fig. 11. Comparison between HFE heights and the critical height at different temperatures.

Even if the values below –5°C are not taken into account, the global behavior of the conductivity remains unusual. It first increases between –5°C and 10°C and then decreases until –60°C. According to theory and to equations (8) and (9), this behavior should be correlated to the viscosity.

$$\kappa = ne / 6\pi\eta r \tag{8}$$

$$\sigma = \sum \rho_i \kappa_i \tag{9}$$

Where κ is the ionic mobility, n is the charge number, e is the charge of an electron, η is the dynamic viscosity, r is the radius of migrating ion, and ρ is the volume charge density for each ionic species i.

However, the results show an opposite behavior. Relying on the kinematic viscosity graph given in the application document of HFE [1] and on equation (5), the variation of the inverse of the dynamic viscosity with temperature is calculated and presented in fig. 12. The increase of $1/\eta$ with the increase of temperature agrees with the expected results of this variation [5]. Equation (8) proves that κ is proportional to $1/\eta$. Therefore, and based on fig. 12, κ increases with temperature rise.

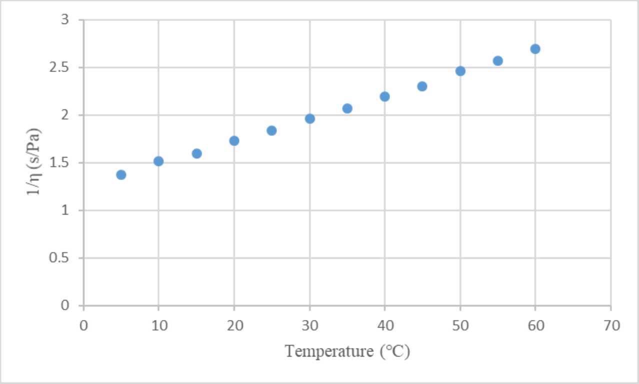

Fig. 12. Inverse of the dynamic viscosity as a function of temperature.

The decrease in conductivity (which leads to the decrease in DF as well) with temperature rise (for the range 5°C-60°C) is unusual [5, 9]. This behavior might be the result of the great decrease in density which reduces the ability of dissociation and hence reduces ρ_i. According to equation (9), if ρ_i decreases with a higher rate than that with which κ_i increases, σ will decrease. Further investigation about this point should be performed.

B. Comparison of Data

Data sheets provide the values of relative permittivity and resistivity at 25°C only [1]. A comparison of those values with the ones calculated based on experimental results shows a clear difference.

TABLE 1: COMPARISON BETWEEN DIELECTRIC PROPERTIES AT 25°C

Property	Reference value	Calculated value
Relative permittivity	7.39	6.72
Resistivity (Ω/cm)	3.29×10^{9}	2.30×10^{10}

This noticeable difference might be due to the fact that the HFE used is old, but more measurements will be conducted to confirm this point.

V. Conclusion

This paper highlights the large influence of temperature on the dielectric properties of HFE-7100. It is important to electrically characterize this liquid at different temperatures due to its promising potential of being used in EHD applications. Two non-typical behaviors have been observed. First a hysteresis behavior at low temperature was observed. It could be due to the liquid density variations. Further work is required where an initial volume of 213 mL (that corresponds to 317 g at 20°C) is filled at the beginning of the experiments in order to keep the electrodes fully immersed at all temperatures. In this way, reliable values of dielectric properties at negative temperatures could be collected. A second and strange behavior has been observed for the conductance value and this phenomenon is not well understood yet. Additional experiments will be conducted to confirm these results.

References

[1] 3M, "Novec™ Engineered Fluid HFE-7100 for Heat Transfer, Application Information," 3M Specialty Materials, 2002. Available on: http://www.dema.net/pdf/3m/HFE-7100.pdf.

[2] 3M, "Novec™ Engineered Fluid HFE-7100, Product Information," 3M Electronics Markets Materials Division, 2009. Available on: http://multimedia.3m.com/mws/media/199818O/3mtm-novectm-7100-engineered-fluid.pdf.

[3] L.V. Badicu, P.V. Notingher, L.M. Dumitran, G. Tanasescu, and D. Popa, "Measuring of the dielectric properties of mineral oil," in Proceedings of the 5th International Conference Metrology and Measurement Systems, pp. 284-289, 2009.

[4] Suwarno and I. S. Darma, "Dielectric properties of mixtures between mineral oil and natural ester," *2008 International Symposium on Electrical Insulating Materials (ISEIM 2008)*, 2008.

[5] J. Muslim, R. Hanna, O. Lesaint, J. L. Reboud, and N. I. Sinisuka, "Electrical characterization of synthetic ester liquid over wide temperature range (−60°C / 200°C)," in 2017 IEEE 19th International Conference on Dielectric Liquids (ICDL), 2017.

[6] International Electrotechnical Commission IEC 61620, "Insulating liquids - Determination of the dielectric dissipation factor by measurement of the conductance and capacitance - Test method," 1998.

[7] Frederick I. Mopsik, "Dielectric Constant of N-Hexane as a function of Temperature, Pressure and Density," Journal of National Bureau of Standards – A. Physics and Chemistry, vol. 71A, no. 4, July-August 1967.

[8] W.G.S. Scaife, "Relative Permittivity of Organic Liquids as a Function of Pressure and Temperature," Journal of Physics A: General Physics, vol. 4, 1971.

[9] EMERSON Process Management, "Theory and Application of Conductivity," EMERSON Process Management, 2010. Available on: http://www2.emersonprocess.com/