Complex Fluids – Thin Porous Materials Interactions revealed via Electrical Impedance Spectroscopy (EIS)

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Abstract

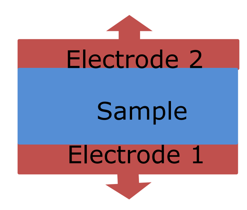
A brief introduction of the EIS technique precedes the presentation of the two experimental setups, with planar and respectively cylindrical electrodes. Home made devices have been employed to study material properties (e.g. dielectric constants) of complex materials as well as physical phenomena as water evaporation of aqueous mixtures, complex liquid transport into porous paper, latex film formation. Each experimental setup was dedicated to a specific process; regarding the dielectric constant measurements, this was possible to be made with both setups and a comparison of the outputs is made.

The EIS method was used for: i) water evaporation from liquid mixtures; ii) liquid penetration into porous paper considering the same liquid and different papers (e.g. thickness), as well the same paper and various liquids.

The dynamics of the physical processes (e.g. evaporation rate, liquid absorption rate, phases in latex film formation) have been studied having time as a parameter. Theoretical models and computational simulations were used to analyze the experimental data and to improve our understanding.

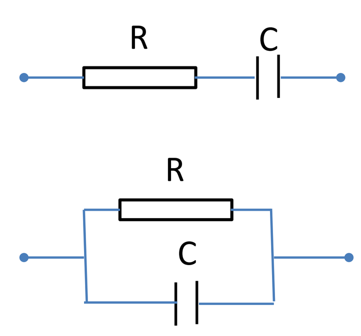
EIS: fundamentals

$$\left.\begin{array}{l} U(t) = U_0 \cdot e^{j(\omega t+\varphi_1)} \\ I(t) = I_0 \cdot e^{j(\omega t+\varphi_2)} \end{array}\right\} \Rightarrow Z = |Z| \cdot e^{j\theta}; \quad \left\{\begin{array}{l} |Z| = \dfrac{U_0}{I_0} \\ \theta = \varphi_1 - \varphi_2 \end{array}\right.$$



Variations of the impedance modulus and argument for series respectively parallel circuits of resistor and capacitor.

	series	ω ⇧	parallel	ω ⇧
|Z|	$\sqrt{R_S^2 + 1/(\omega^2 \cdot C_S^2)}$	⇩⇔	$R_P/\sqrt{1+\omega^2 \cdot R_P^2 \cdot C_P^2}$	⇩
arg Z	$1/(\omega \cdot R_S \cdot C_S)$	⇩	$\omega \cdot R_P \cdot C_P$	⇧

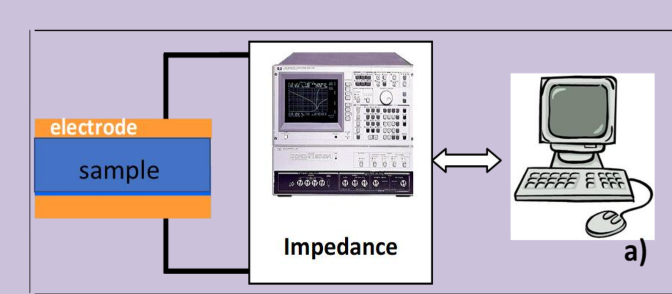


$Z_i = R_i + jX_i$, i=1, 2, eq

$$\left\{\begin{array}{l} R^s_{eq} = R_1 + R_2 \\ X^s_{eq} = X_1 + X_2 \end{array}\right. \quad \text{parallel} \rightarrow \quad \leftarrow \text{series} \quad \left\{\begin{array}{l} R^p_{eq} = \dfrac{(X_1 \cdot R_2 + X_2 \cdot R_1)\cdot(X_1+X_2) + (R_1\cdot R_2 - X_1 \cdot X_2)\cdot(R_1+R_2)}{(R_1+R_2)^2 + (X_1+X_2)^2} \\ X^p_{eq} = \dfrac{(X_1 \cdot R_2 + X_2 \cdot R_1)\cdot(R_1+R_2) - (R_1\cdot R_2 - X_1 \cdot X_2)\cdot(X_1+X_2)}{(R_1+R_2)^2 + (X_1+X_2)^2} \end{array}\right.$$

Experimental setups

a) Planar electrodes

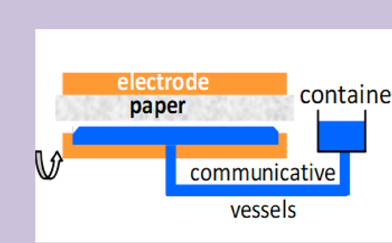


RC parallel

$$C = \frac{\varepsilon_0 \cdot \varepsilon_r \cdot A}{d}$$

$$R = \frac{\rho \cdot d}{A}$$

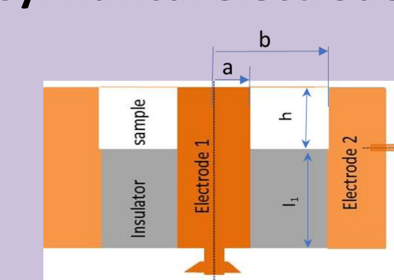
- Material characterization: ε_r *and* ρ



Two series of RC parallel

- Process study: *liquid imbibition into porous media*

b) Cylindrical electrodes



Multi RC parallel

$$C = \frac{2\pi\varepsilon_0 \cdot \varepsilon_r}{Ln(b/a)} \cdot h$$

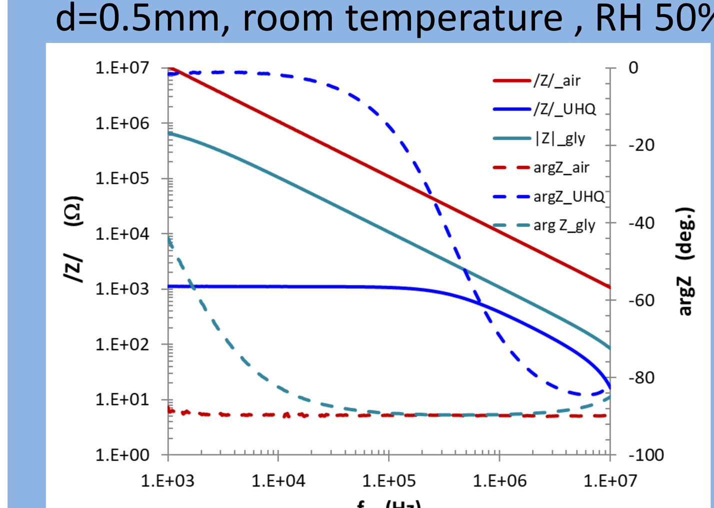
$$R = \frac{\rho}{2\pi \cdot h} \cdot Ln(b/a)$$

- Material characterization: ε_r *and* ρ
- Process study: *water evaporation*

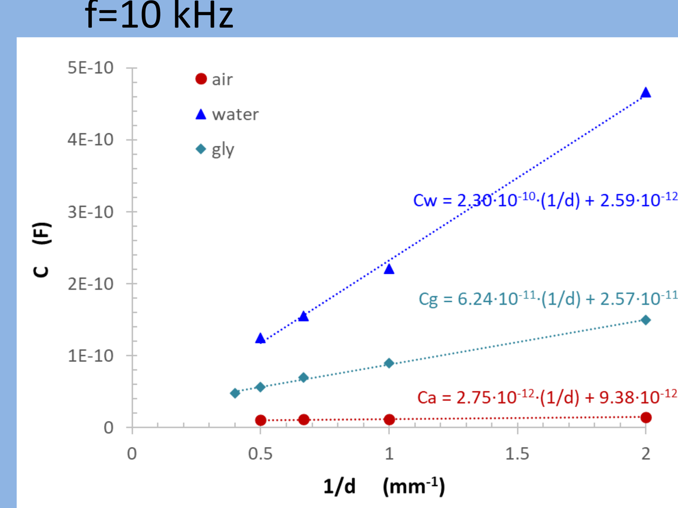
Results: material characterization

i) Material characterization: setup (a)

d=0.5mm, room temperature , RH 50%



f=10 kHz



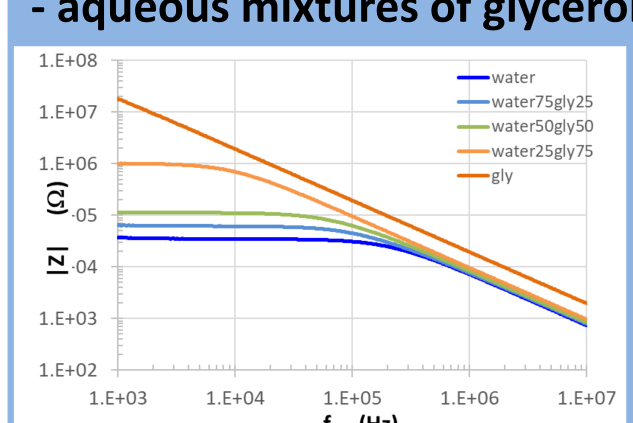
ε_r^w = 80.76

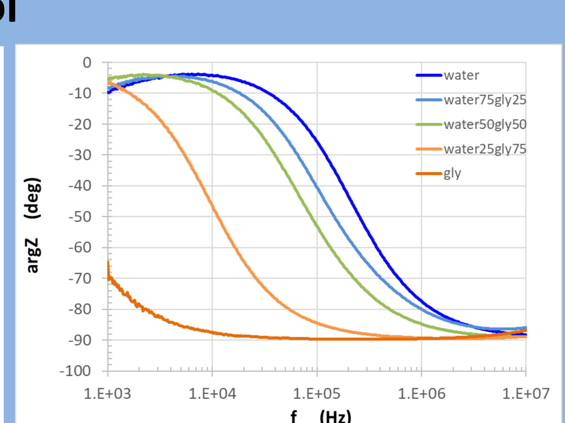
ε_r^g = 23.84

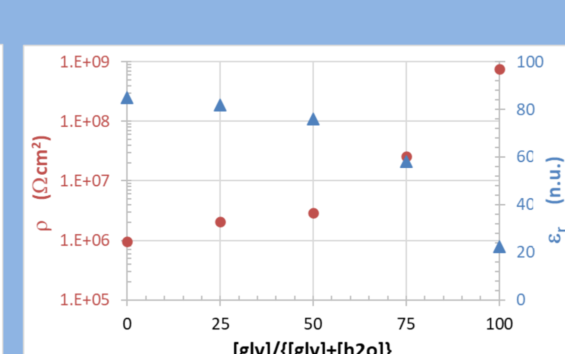
Dielectric const. for liquids or solids layers

ii) Material characterization: setup (b)

- aqueous mixtures of glycerol



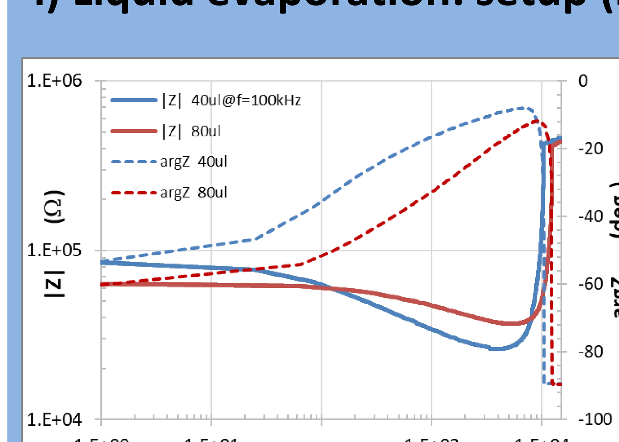


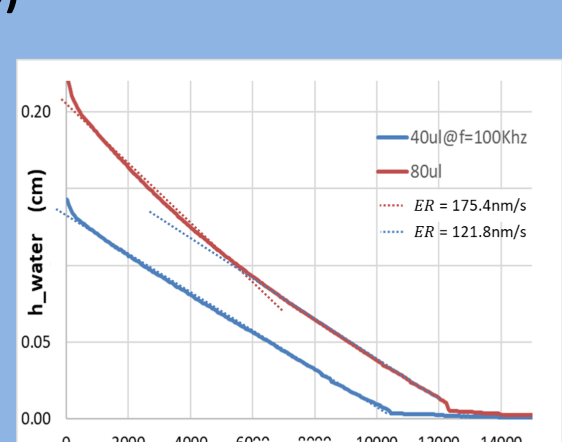


Complex liquids characterized: dielectric & electrical properties

Results: processes dynamics

i) Liquid evaporation: setup (b)

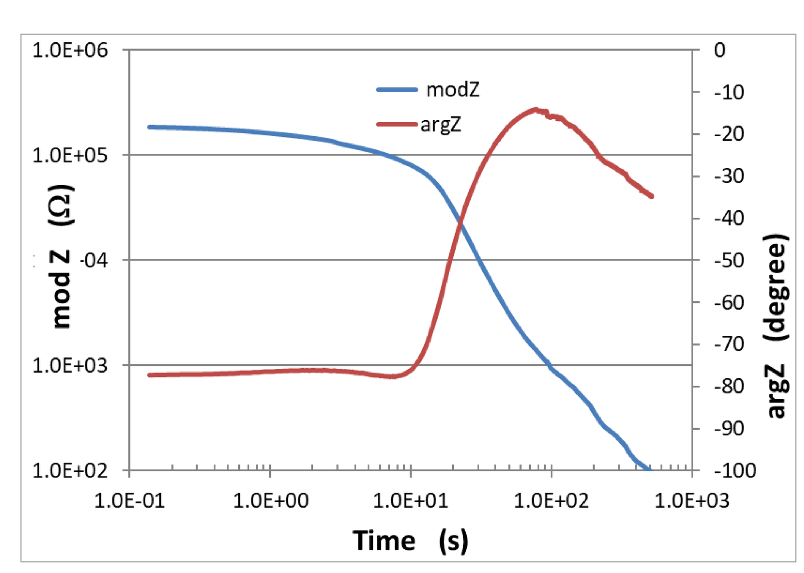


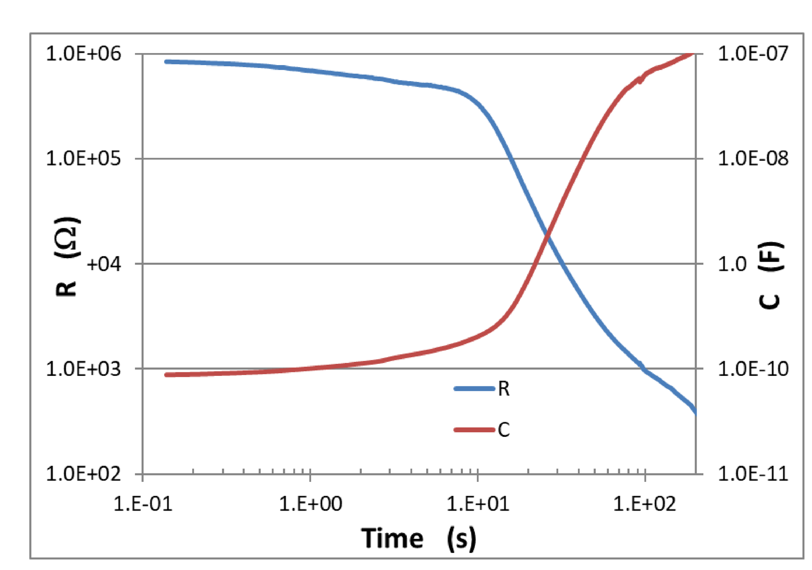


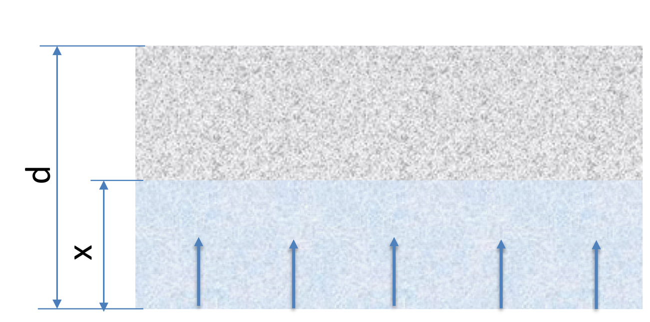
- Two rates of evaporation (ER) caused by limitation of vapor diffusion due to cell geometry

Results: Processes dynamics

ii) Water imbibition into porous paper: setup (a) adapted



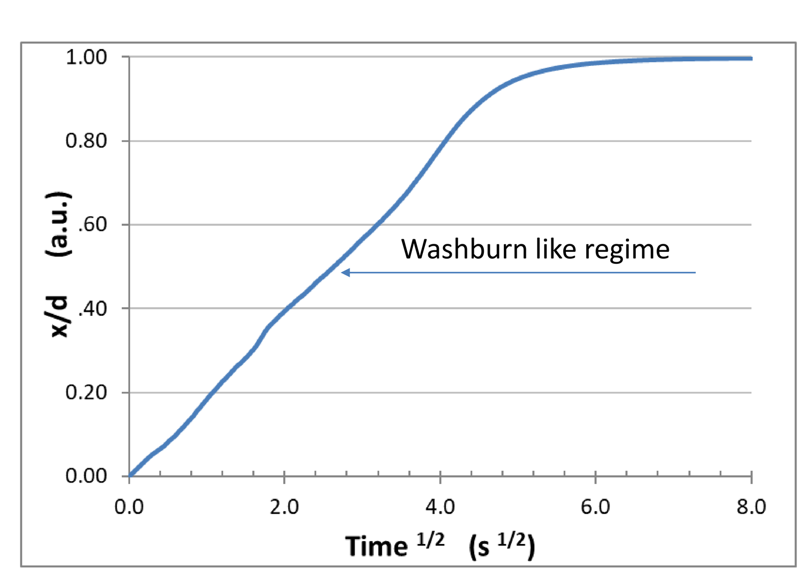




Assuming the liquid front is parallel to the electrodes surface and considering two impedances in series, each impedance being a RC parallel circuit:

$$1 - \frac{C_0}{C_x} = \frac{x}{d} \cdot \left(1 - \frac{C_0}{C^*}\right)$$

where $C_0 = C_{t=0}$; $C_x = C_{t=t_x}$; $C^* = C_{t=t_{max}}$



Slope = 0.197 $s^{-1/2}$

$$\text{Imbibition speed} \sim \left\{\begin{array}{ll} 11.8\,\mu/s & 0 < t < 3s \\ 3.2\,\mu/s & 5 < t < 16s \end{array}\right.$$

LIMITATIONS of the EIS METHOD:

i) the dielectric constant of the liquid versus porous material must be different;
ii) in the EIS data analysis the front of the liquid moves parallel to the electrodes' surface;
iii) by the experiment preparation the edge effects of the cell can be minimized.

Conclusions:

EIS is a simple, rapid and direct measurement to investigate the dielectrical properties of materials, which was proofed for simple and complex liquids, for solid layers and for two phases samples (solid-gas, solid-liquid). Using special designed measurement cells, the dynamics of physical processes as water evaporation from aqueous mixtures and liquid penetration into porous paper were successfully investigated. The EIS measurement method proved to be a useful technique within the experimental limits as have been here demonstrated.