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### ► To cite this version:

Mohammad Ali Iravani, Hossein Davarzani, Jacques Deparis, Stéfan Colombano, Nicolas Philippe, et al.. Experimental study of electrical complex resistivity in a 2D multiphase porous medium under non-isothermal conditions: application to soil remediation monitoring. Near Surface Geophysics, European Association of Geoscientists and Engineers (EAGE), 2022. hal-03813495

**HAL Id: hal-03813495**

**<https://hal-brgm.archives-ouvertes.fr/hal-03813495>**

Submitted on 22 Nov 2022

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# Experimental study of electrical complex resistivity in a 2D multiphase porous medium under non-isothermal conditions: application to soil remediation monitoring

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Running title: Induced polarization under non-isothermal conditions

## Highlights

- Proper application of spectral induced polarization (SIP) in samples polluted by dense non-aqueous phase liquids (DNAPL)
- Temperature and saturation separately affect electrical complex resistivity
- Temperature has a considerable effect on Cole-Cole parameters in a 2D tank
- Saturation changes have a remarkable impact on phase shift
- 2D tank results on complex resistivity confirm 1D cell findings

## **Abstract**

In this decade, electro-geophysical methods are widely used in different environmental subjects. Study on soil remediation polluted by DNAPLs has become a certain need for all countries. Geoelectrical methods show their potential to facilitate evaluating decontamination processes. Our challenge in this study was to understand how coupled temperature and saturation changes affect electro-geophysical parameters in a contaminated 2D sample. The primary objective was to evaluate the efficiency and potential of spectral induced polarization (SIP) for monitoring the recovery of dense non-aqueous phase liquids in contaminated porous media. A set of 2D tank experiments investigated the impacts of temperature and saturation changes on the electrical complex resistivity of a saturated porous medium under non-isothermal conditions. The measurements were made with a coal-tar and water fluid pair in a porous medium that has been simulated by 1 mm glass beads. We circulated hot water around the tank and used an immersion heater to heat the porous medium in the tank at different stages. The SIP technique (also called complex resistivity) was used to measure the complex electrical resistivity of a medium in the frequency domain. The experimental results for a simple drainage case were validated using numerical modeling. The complex electrical resistivity was used to obtain the saturation field before and after imbibition. For this purpose, the generalized Archie's law obtained for the same fluid pair with 1D cells (with a vertical flow) was used. Our results from electrical resistivity measurements for saturation fields are in accordance with 2D tank images and can illustrate the saturation change with pointwise resistivity measurements. The results show that saturation change has the main role in electrical resistivity variation compared to temperature (5 to 7%). We also studied the effects of temperature change on the Cole-Cole parameters and the results confirm our previous findings with the same variation trend in these parameters. The results from varying electrical complex resistivity from the 2D tank (with vertical and horizontal flow) in the laboratory

conditions will help us to understand the coupled temperature and saturation effects on complex resistivity in a real polluted site case.

\*Keywords

Induced polarization, modeling, pollution, resistivity, environmental

## 1 Introduction

2 Pollution of soil due to dense non-aqueous phase liquid (DNAPL) spilling has become a  
3 crucial issue of concern during the last decade, causing numerous geo-environmental (e.g.,  
4 mitigation of DNAPLs on aquifers) problems (Habiyakare et al., 2022). In polluted sites,  
5 DNAPLs sink below the water table and cause dissolved plumes in the subsurface (Pankow  
6 and Cherry, 1996; Power *et al.*, 2014). After many years of research, soil contamination due to  
7 DNAPLs is still one of the main challenges for the environmental and geophysical  
8 communities (Kavanaugh, Suresh and Rao, 2003). DNAPLs, including coal tar (CT),  
9 contaminate soils and water widely when released in the subsurface, mainly from industrial  
10 parks. DNAPLs are part of a group of immiscible fluids that pass through the saturated and  
11 unsaturated zones due to gravity and capillary forces, via migration passages made of pores,  
12 until stopping at an impermeable stratum (Illangasekare *et al.*, 1995; Power *et al.*, 2014).  
13 Various remediation techniques can be used in these sites to depollute them. These include  
14 pump and treat, thermal, bioremediation, and chemical methods (Beyke and Fleming, 2005;  
15 Hadley and Newell, 2012). Pump-and-treat is the common and first remediation technique to  
16 remove the free product. After pumping, the residual saturation can be removed using  
17 biochemical remediation techniques.

18 Geophysics has shown the value of the long-term monitoring of clean-up processes (e.g.,  
19 Brewster *et al.*, 1995; Wilson *et al.*, 2009). Of all the geophysical methods, electromagnetic  
20 methods and especially electrical methods are useful for studying the processes involved  
21 during clean-up and degradation of pollutants (Chambers *et al.*, 2004; Mao *et al.*, 2016; Deng  
22 *et al.*, 2020), 3D imaging of a jet fuel spill (Orozco *et al.*, 2021; Helene, Moreira and Bovi,  
23 2020). The electro-geophysical methods, especially direct current (DC) resistivity, induced  
24 polarization (IP) techniques, and spectral induced polarization (SIP) have proved their  
25 potential in geological conditions, in saturated conditions (e.g., Weller, Nordsiek and

26 Debschütz, 2010; Slater *et al.*, 2014; Revil *et al.*, 2015; Kremer *et al.*, 2016b; Sparrenbom *et*  
27 *al.*, 2017), unsaturated conditions (e.g., Mainault, Jougnot and Revil, 2018), oil, gas, and  
28 mining industries (e.g., Friedrichs *et al.*, 1999), soil pollution and remediation monitoring  
29 (e.g., Pearce and Zuluaga, 2004; Ling and Zhang, 2017; Liao *et al.*, 2018) and civil  
30 engineering (e.g., Susanto *et al.*, 2013). In a multiphase porous medium, various combinations  
31 of different parameters such as temperature, saturation, level of compaction, and pore fluid  
32 properties can have a similar effect on the measurements (e.g., Sen and Goode, 1992; Denicol  
33 and Jing, 1998). Therefore, studying the effect of each parameter to determine their role and  
34 ideally, their related simultaneous effects on geophysical parameters is necessary.

35 Sadowski (1988) performed the first laboratory study on different clay samples with  
36 different pollutants and different concentrations. He found that the SIP method could be used  
37 to identify organic contaminants in clayey soils for different concentrations. Börner, Gruhne  
38 and Schön (1993) contributed to laboratory research on the effects of organic liquid  
39 contaminations on different rock types and sandstones. They demonstrated that both the real  
40 and imaginary parts of complex resistivity are affected by the properties of the contaminant  
41 filling the pores. They noted that in some cases the various contaminants could be  
42 differentiated using the imaginary part and emphasized the effect of interactions between pore  
43 fluid characteristics and pores' internal surface structure.

44 The existence of organic contamination can affect capacitive conduction in the IP  
45 response due to the surface reaction between contamination and soil grains (Vaudelet *et al.*,  
46 2011). IP responses in these contaminated soils are related to the saturation (Breede *et al.*,  
47 2012), distribution, concentration, and types of contaminants present in soil (Kemna *et al.*,  
48 2012). Previous studies demonstrate that the presence of contaminants (Gasoline and leachate  
49 results of acidification by organic and carbonic acids) in the soil increases resistivity (Benson,  
50 Payne and Stubben, 1997; Sauck, 2000). Martinho, Almeida and Matias (2006) reported an

51 increase in chargeability due to the presence of pure organic contaminations (gasoline,  
52 isopentane, toluene, and benzene) in clayey soil. Many studies based on the SIP method have  
53 shown an increase in amplitude and phase shift due to the existence of hydrocarbons (Vanhala,  
54 Soininen and Kukkonen, 1992; Börner *et al.*, 1993; Schmutz *et al.*, 2010). However other SIP  
55 studies reported a decrease in amplitude and phase shift in different media consisting of  
56 different pure and dissolved hydrocarbons (Weller and Börner, 1996; Vanhala, 1997; Revil,  
57 Schmutz and Batzle, 2011).

58         Recently, Iravani *et al.* (2020a, 2020b) evaluated how temperature and saturation  
59 changes in two DNAPLs (coal tar and chlorinated solvent) affect complex electrical resistivity  
60 and relative permittivity. They used an oven to study temperature change and a 1D drainage-  
61 imbibition system to study how saturation changed these two parameters. They carried out  
62 experiments in cylindrical cells filled with glass beads (to simulate soil/porous media) and  
63 saturated with water and CT. The relationship between electrical resistivity and relative  
64 permittivity with saturation was investigated for two different coupled immiscible fluids,  
65 water/coal-tar and canola oil/salty ethanol. They found that temperature changes these two  
66 geophysical parameters linearly for the coal tar (CT) and chlorinated solvent coupled with  
67 water. The effect of saturation change was not linear, and they did state that the generalized  
68 Archie's law could fit their experimental data well. Colombano *et al.* (2020) investigated the  
69 relationship between resistivity and saturation for chlorinated solvent. They used a drainage-  
70 imbibition protocol to monitor electrical resistivity and permittivity. Their objective was to  
71 estimate residual saturation indirectly. They used the complex refractive index model (CRIM)  
72 and generalized Archie's law to model their permittivity and resistivity data, respectively.  
73 They reported that estimated electrical resistivity presented less correlation with the  
74 experimental data compared to permittivity. They concluded that temperature and saturation  
75 affect the electrical resistivity and relative permittivity of the medium. Colombano *et al.*

76 (2021) investigated the imbibition of a mixture of chlorinated solvents by thermal and  
77 chemical enhancements (Colombano *et al.*, 2021). They found that the temperature has no  
78 effect on DNAPL recovery that could be linked to the actual properties of the oils. However,  
79 coal tar is more viscous than most chlorinated solvents. Moreover, the dynamic viscosity of  
80 coal tar decreases significantly with temperature (Philippe *et al.*, 2020). To the best of our  
81 knowledge, no other work is reported on electrical resistivity measurements for coal tar.

82 Blondel *et al.* (2014) compared lab and field results in clayey and clayey-silt soils. They  
83 quantified a resistivity increase, normalized chargeability, and decreased resistivity in  
84 measurements with oil not degraded. When it is partially degraded they saw no changes in the  
85 phase-lag and chargeability parameters. Gourry, Jeannot and Proust (2001) also showed that  
86 under certain conditions, oil pollution like this can increase chargeability because of high  
87 resistivity and it is rather related to wettability. This statement was not confirmed by Blondel  
88 *et al.* (2014).

89 Orlando and Palladini (2019) carried out a series of laboratory tests to study how  
90 resistivity and permittivity vary in a 2D cell in a multiphase (two-phase) system. The  
91 contamination they used was HFE-7100 (hydrofluoroether) in saturated (with pure, dissolved,  
92 and gaseous phases) grained glass bead (GB) porous media. They used geophysical  
93 measurements and physico-chemical constraints to monitor these parameters over a long  
94 period. Different geophysical techniques were used to propose empirical models to monitor  
95 water saturation in a multiphase porous media contaminated by DNAPL. Photographs were  
96 used to confirm the geophysical data. Low frequency IP can detect the pure HFE-7100 phase.  
97 In another study, Orlando and Renzi (2015) studied how electrical resistivity varies in ground  
98 due to the existence of DNAPL in a laboratory study. Like Orlando and Palladini (2019), they  
99 used a GB-packed medium contaminated with HFE-7100 in a saturated condition. They found  
100 that different DNAPL phases have different impacts on the physico-chemical characteristics of



101 the contaminated medium. In their study, free and dissolved DNAPL caused a change in  
102 electrical resistivity. They concluded that electrical resistivity coupled with the GPR technique  
103 can be used for characterizing the contaminated sites because neither technique could be  
104 sensitive enough for a long time.

105 It is known that the presence of organic contaminants modifies the impedance of the fluid-  
106 grain interface through clay polymerization (Olhoeft, 1985; Vanhala, 1997). The presence of  
107 organic pollutants as free phase changes the distribution of the conductive aqueous phase in  
108 the pore space (like air can do in unsaturated media). As SIP response changes with varying  
109 water/air saturation (e.g., Ulrich and Slater, 2004; Titov et al., 2004; Binley et al., 2005,  
110 Maineult et al. 2018), free-phase hydrocarbons should also produce a measurable SIP effect. A  
111 few studies have been conducted on complex resistivity laboratory measurements either on  
112 artificially contaminated soil or rock samples or on field samples from contaminated sites.  
113 Even though the results differ in the observed effects, they proved that the SIP response of  
114 soils and rocks is measurably influenced by hydrocarbon contamination. However, a detailed  
115 understanding of how contamination affects SIP response is still lacking. Many studies did not  
116 pay sufficient attention to controlling the nature or distribution of contaminants in the porous  
117 media, and on assessing independently the effects of dissolved, adsorbed, and free-phase,  
118 leading sometimes to what appear to be contradictory results. Here, we assumed that the SIP  
119 response of the contaminant obeys a law similar to what Vaudelet et al. (2011) observed above  
120 a plume of chlorinated solvents, i.e., a Cole-Cole like behavior.

121 The study of geophysical parameters during remediation by the thermal enhanced  
122 method is influenced by two environmental parameters: temperature due to soil heating  
123 (Iravani *et al.*, 2020a, Philippe *et al.*, 2020) and saturation changes (Iravani *et al.*, 2020b;  
124 Colombano *et al.*, 2020) due to contamination pumping. In previous studies, we separately

125 investigated the impact of temperature and saturation on electrical resistivity in contaminated  
126 saturated porous media with CT (Iravani *et al.*, 2020a, 2020b).

127 In this study, we investigated the coupling of transient heat transfer in multiphase flow  
128 with saturation variation in a 2D tank. No work to date has studied transient temperature  
129 transfer and saturation changes at the same time in 2D due to its complexity. Heating in the 2D  
130 tank mimics the soil heating in the field by increasing the temperature of pollutants to decrease  
131 their viscosity. These phenomena increase pollutant mobility and so increase the pumping rate  
132 of contamination in saturated soil during depollution. Heating the samples also changes the  
133 geo-electrical parameters. The goal of the current study is to determine the saturation field in  
134 the 2D tank from resistivity measurements. All these experimental studies have been done to  
135 implement the SIP for monitoring the real remediation process of DNAPLs in the field.

136 It is worth noting that one of the main challenges in the monitoring of the subsurface with  
137 geophysical methods is that there are few methods (e.g., boreholes) for verifying the recorded  
138 geophysical response of the medium to validate the remediation process (Spies, 1996; Keys,  
139 2017).

## 140 Theoretical background

### 141 Spectral-induced polarization mechanisms

142 SIP is an extension of the IP method with alternating current (AC) in the frequency  
143 domain. SIP is used to study the ratio and phase shift between voltage and current of the  
144 subsurface or a sample. Generally, electrical polarization in the range of studied frequencies  
145 (i.e., from 0.01 to 10,000 Hz) has four main mechanisms including electrode polarization,  
146 membrane polarization, Maxwell-Wagner polarization, the polarization of the diffuse layer  
147 (electrical double layer, EDL) including the Stern layer polarization (e.g., Kemna *et al.*, 2012).

148 This study does not separately investigate the different mechanisms involved to characterize  
149 the effect of CT saturation and temperature changes.

### 150 Electrical complex resistivity

151 The electrical resistivity ( $\rho$ ) in a homogeneous sample can be obtained by multiplying  
152 resistance (R) and a geometric factor (K) related to the position of the electrodes (for current  
153 injection and voltage measurement). The complex electrical resistivity reads (e.g., Guéguen  
154 and Palciauskas, 1994; Ghorbani, 2007; Glover, 2015):

$$\rho_{(f)} = \rho'_{(f)} - i\rho''_{(f)} = |\rho_{(f)}| \exp(i\varphi) \quad (1)$$

155 where  $\rho'$  and  $\rho''$  are, respectively, the real and the imaginary parts of complex resistivity and  
156  $|\rho_{(f)}|$  and  $\varphi$  are the amplitude and the phase shift of the resistivity response (for low phase,  
157 below a few hundred of mrad, can be simplified as  $\varphi \approx \rho''_{(f)}/\rho'_{(f)}$ ). These equations can be  
158 written in terms of the electrical conductivity,  $\sigma_{(f)}$  (S.m<sup>-1</sup>) which is the inverse of the electrical  
159 resistivity.

160 A very first relationship to study the effect of temperature on electrical resistivity was  
161 presented by Dakhnov (1962) as:

$$\rho_w = \frac{\rho_{w0}}{1 + \alpha(T - T_0)} \quad (2)$$

162 where  $\rho_w$  is the resistivity of water at temperature  $T$  and  $\rho_{w0}$  is the resistivity of water at the  
163 initial temperature  $T_0$ , and  $\alpha$  is the temperature coefficient of resistivity (see Iravani et al,  
164 2020a, for instance). We used equation (2) to obtain  $\alpha$  value for our experiments using  
165 thermocouples, with a reference temperature of  $T_0=20^\circ\text{C}$ , where  $T$  is the temperature measured  
166 by thermocouples, and  $\rho_{w0}$  is the averaged measured resistivity at  $20^\circ\text{C}$ . This linear  
167 relationship was defined for water but can be used for DNAPL mixtures (Iravani *et al.*, 2020a).

168 In the literature, no universal model has been presented with the consideration of the  
169 physico-chemical properties of each phase in a multiphase system in regard to the frequency

170 changes. The lack of a developed comprehensive model on this subject steers researchers to fit  
 171 the experimental data of complex resistivity with the phenomenological models. One of the  
 172 most used phenomenological models is presented by Cole and Cole (1941) and was derived  
 173 from the Debye (1929) model, which was firstly developed for relative permittivity (Pelton *et*  
 174 *al.* 1978).

175 Pelton *et al.* (1978) proposed a model for SIP spectra that exchanged relative  
 176 permittivity with electrical complex resistivity for practical applications that describes

$$\rho(\omega) = \rho_0 \left[ 1 - m \left( 1 - \frac{1}{1 + (i\omega\tau)^c} \right) \right] \quad (3)$$

177 where  $\rho_0$  is the low-frequency resistivity,  $c$  is the so-called Cole-Cole exponent,  $m$  is the  
 178 chargeability, and  $\tau$  is the mean relaxation time ( $m$  and  $c$  can be in the range of 0 and 1). If  $c$   
 179 equals 1 this equation will be similar to the Debye model. For this study, the Cole-Cole model  
 180 was chosen because it has been demonstrated to be a good model to represent empirically the  
 181 polarization of single grains or pores (e.g., Leroy *et al.* 2008; Niu & Revil 2016).

182 In this study for saturation prediction, the generalized Archie's law, which is developed  
 183 by Glover (2010) based on the classical Archie's law (Archie, 1942), was used. It is defined as  
 184 below

Archie's law 
$$\sigma_{mixed} = \sigma_{(f)} \Phi^m \quad (4)$$

185 and

Generalized Archie's law 
$$\sigma_{mixed} = \sum_{i=1}^n \sigma_i \Phi_i^{m_i} \quad (5)$$

186 where  $\sigma_{(f)}$  (S/m) is the conductivity of the liquid inside the pores,  $\Phi$  is the porosity,  $i$  is the  
 187 indication of each phase and  $m$  is the cementation exponent.

188 In this study, we validate mixing models and calibration curves obtained from the  
 189 previous study in cells and columns (Iravani *et al.*, 2020a, 2020b) using a 2D two-phase flow

190 and comparing the results with imaging for validation. In a previous study, Iravani *et al.*  
191 (2020a) showed both resistivity and phase are related to the temperature variation in 1D  
192 columns. They found a linear relationship between temperature and resistivity. By using the  
193 Cole-Cole model they also found that temperature affects the frequency domain. Iravani *et al.*  
194 (2020b) studied the saturation impact on the magnitude and phase of electrical complex  
195 resistivity. They reported the generalized Archie's law was applicable to study the multiphase  
196 medium contaminated by CT. They found that saturation change has a direct impact on  
197 electrical resistivity.

## 198 **Material and methods**

199 A laboratory-scale experiment was carried out to study temperature and saturation  
200 effects on complex electrical resistivity during the drainage and imbibition of DNAPLs in a  
201 2D tank. The experiment was done in a saturated porous medium with an immiscible liquid  
202 pair (CT and water). In the following, we describe the essential points, experimental setup, and  
203 procedures used for this experiment.

### 204 **2D tank setup**

205 The 2D tank has dimensions of 30 cm × 50 cm × 7 cm (height, width, depth). A  
206 schematic form of the front, back, and top of the tank is shown in Figure 1. The body of the 2D  
207 tank is made of a solvent resistant material called polyvinylidene fluoride (PVDF). The front  
208 wall of the tank with a thickness of 0.8 cm is made of a transparent glass rectangle through  
209 which pictures are taken at each stage.

210 A stainless-steel heating element was inserted inside the left-side of the tank to produce  
211 the non-isothermal condition. Fourteen type K thermocouples (green circles) record  
212 temperatures in the tank. The thermocouples were connected to a Campbell CR-1000  
213 acquisition system. The temperatures were measured with sampling intervals of 30 s. For the

214 SIP measurements (Figure 1c), black and blue circles represent 30 current and 30 potential  
215 electrodes, respectively, 5 cm apart from each other. The electrical AC is injected between two  
216 stainless steel current electrodes (diameter=65 mm) made of nickel-cobalt alloy (MP35N) and  
217 the response voltage is measured between two handmade non-polarizable potential electrodes  
218 (Cu/CuSO<sub>4</sub>) with a diameter of 1 cm. Non-polarizable electrodes are used in SIP studies to  
219 measure the voltage response of an injected current in a medium (e.g., Kremer *et al.* 2016a;  
220 Abdulsamad *et al.*, 2016). In non-polarizable electrodes, current can freely pass without  
221 polarization. Among common electrode solutions, Cu/CuSO<sub>4</sub> was chosen based on the method  
222 proposed by Mainault, Bernabé and Ackerer (2004). The solution was made using a mixture of  
223 72.75 g of milli-Q water (ultrapure water), 26 g of CuSO<sub>4</sub>, and 1.25 g of gelatin in 100 g of  
224 solution. A heating shaker was used to mix the solution for one hour at 80°C.

225 The non-polarizable electrodes were placed outside the samples to avoid inflow  
226 interference that in turn can interfere with electrical current signals (Mainault *et al.*, 2004). A  
227 porous ceramic (Ameteksi scientific instruments) was used in the interface of non-polarizable  
228 electrodes and the saturated porous media. Each non-polarizable electrode was connected to  
229 the SIP-lab IV (manufactured by Radic Research) with a shielded cable to avoid contamination  
230 of the data due to electromagnetic coupling (Mainault *et al.*, 2004; Bagotsky, 2005).

231 Glass beads (GB) made of silica with a diameter of 1 mm, forming a pack with a  
232 porosity of  $40\% \pm 2\%$ , were used as a porous medium. Different GB sizes were tested and this  
233 size was chosen to simulate a porous medium in the lab with close physical properties to field  
234 soil (e.g., the grains size and the porosity of the medium). The tap water was degassed using an  
235 ultrasonic tank (VWR Ultrasonic Cleaner - USC500D). For obtaining temperature variation  
236 effects in a non-isothermal condition, an immersion heater heats from the left side of the tank,  
237 and heat transfers to the right side. In non-isothermal conditions, there is a possibility of  
238 studying the temperature and saturation changes at the same time based on how temperature

239 varies across the different halves of the tank and how saturation varies during imbibition from  
240 the bottom middle of the tank.

241 Water is injected using five pipes located at the bottom of the tank with the possibility of  
242 cutting fluid currents by using clips and clamps. The pipes are numbered and connected to a  
243 peristaltic pump (Watson Marlow 530U). The tank is filled step by step by first filling 5 cm  
244 bottom layer of well spread GB and then water was injected until the porous medium was fully  
245 saturated. This procedure should be carried out with great patience to avoid any air bubbles  
246 being captured inside the porous network. These bubbles, especially when they are connected  
247 to electrodes or thermocouples, can cause significant measurement errors. This operation is  
248 repeated step by step until reaching the top of the 2D tank and when all electrodes were buried  
249 by GB and water (almost 27.5 cm). A camera is placed on a fixed tripod in front of the 2D  
250 tank. Photos were taken during increasing CT levels and imbibition at regular time intervals of  
251 three and one minutes, respectively.

252 Previous experiments using imaging, time-domain reflectometry (TDR), and mass  
253 balance analysis showed a 2D flow behavior (Colombano *et al.*, 2021). However, the character  
254 of the electric field can be in 3D, and therefore, our numerical model uses a 3D geometry (with  
255 a small thickness) to simulate electrical fields.

## 256 [Experimental and measurement procedure](#)

257 Twenty-seven SIP measurements of an equatorial dipole-dipole (EDD) array were  
258 performed to resolve the variations of the electrical resistivity within the 2D tank. The  
259 conventional location of measurement for an EDD array is in the middle of the rectangles in  
260 Figure 1c. The exact place of measurements with the EDD array is illustrated in Figure 2 with  
261 blue circles and the number of measurements. Before and after each experiment,  
262 measurements were made with tap water to examine the performance and accuracy of  
263 electrodes and calculate the geometric factors (K). The geometric factor for water is easy to

264 obtain because the resistivity of water is homogeneous and can be measured by a portable  
265 conductivity meter and the resistance by SIP lab. Then we calculated the K factor from  
266 resistivity over resistance. To validate the work, the measured geometric factors should be  
267 close to each other. According to our experience, the non-similarity of the geometrical factors  
268 was mainly related to non-polarizable electrodes or their surroundings. A blank test (with  
269 water only) was done for at least 24 hours to have enough data to increase measurement  
270 accuracy. The measurement readings may have serious errors, because of air trapping inside  
271 the polarizable electrodes. With a simple test with only water, these deficit electrodes can be  
272 replaced. In the next step, the experimental geometric factors (K) must be compared with ones  
273 that will be estimated by a numerical model for all 27 SIP measurements.

274         After creating a stable porous medium saturated with water, CT was injected from the  
275 bottom of the 2D tank (using the same points of entry where water was injected). For each step  
276 of increasing DNAPL content, measurements were made until the DNAPL has been reached to  
277 the middle of the 2D tank at 15 cm. This procedure was repeated three times to obtain a  
278 horizontal interface between CT and water in the middle of the tank. In the experimental  
279 process, obtaining a perfect flat boundary with CT was not easy due to fingering and dissimilar  
280 distribution in the different parts of the 2D tank. After stabilizing the experimental setup with  
281 the portion of half GB+water and the other half GB+CT, SIP measurements were made before  
282 heating, in the frequency range of 0.183 Hz to 20 kHz. Resistivity and temperature were  
283 measured at all levels in the 2D tank.

284         After heating the tank from the left side and diffusing the heat to the right side of the  
285 tank, our experimental protocol was done for drainage and imbibition of water where SIP  
286 measurements were conducted at each step. The heating time takes almost 12 hours to have a  
287 stable temperature in each thermocouple (measurement zone) of the tank. When the recorded  
288 temperature was stable, the pumping of CT from the bottom middle of the tank was started.



289 Due to the rapid imbibition, it was not possible to measure more than two frequencies during  
290 this dynamic stage of the experiments. Therefore, during the imbibition period, the SIP spectra  
291 were recorded in two frequencies (1.46 Hz and 2.92 Hz), close to the ones used commonly in  
292 the field scale. The resistivity calculations were, therefore, based on a single-frequency  
293 approach.

294 Iravani *et al.* (2020a) reported the  $\alpha$  values (equation (2)) for the same liquids (water  
295 and CT) with and without GB in 1D cells and columns. From their comparison between the  $\alpha$   
296 value of water with other studies, normally the  $\alpha$  value should be almost the same. We  
297 calculated this value again using our 2D tank experimental data to be sure it was the same in  
298 this new 2D configuration. In three levels of measurements, the top level is filled with  
299 GB+water and the bottom level with GB+CT. Figure 3 is the linear regressions of the  
300 resistivity data with the temperature where the y-axis is the ratio of the resistivity at reference  
301 temperature ( $T_0=20^\circ\text{C}$ ) and resistivity at T ( $\rho_0/\rho$ ) minus 1, and the x-axis is the temperature  
302 difference ( $T - T_0$ ). The slopes of the linear regression of the 9 measurements at the top with  
303 GB+water and the bottom GB+CT are presented in Figure 3a and Figure 3b. The obtained  
304 regression is in accordance with the previous finding by Iravani *et al.* 2020a,b. Hayashi (2004)  
305 studied the linear relationship between electrical conductivity and temperature that was usually  
306 used in previous studies on water with different salinity and chemical substances. Regardless  
307 of the compositional and structural differences, the relationship between these two parameters  
308 of all different water samples was linear. He suggested being more cautious if temperature  
309 values are dissimilar to the reference temperature of 25 °C. The  $\alpha$  values for water-saturated  
310 GB (0.052) and CT saturated GB (0.075) are the same as what we found in columns (Iravani *et*  
311 *al.*, 2020a) but the coefficients of determination are less (GB+water 13.09% and GB+CT  
312 3.28%) than columns for both.

313 According to Iravani et al. (2020b), the final equations for correcting resistivity for both  
314 multiphase systems are:

$$\rho_{(GB+water)} = \rho_{0(GB+water)} / (1 + 0.052(T - 20)) \quad (6)$$

$$\rho_{(GB+CT)} = \rho_{0(GB+CT)} / (1 + 0.075(T - 20)) \quad (7)$$

315 After validating  $\alpha$  values in two different geometries and despite the complexity of CT  
316 components, these two equations can be used in our 2D tank for temperature correction of  
317 electrical resistivity in the multiphase system of GB+CT and GB+water. The porous medium  
318 in the tank was subjected to heating with an immersion heater. The temperature fields (back  
319 view) in the tank before and after imbibition are shown in Figure 4. We used Surfer software  
320 to interpolate the data. Surfer interpolated the temperature and the corrected resistivity in the  
321 range of 110 to 100,000  $\Omega.m$  with the Kriging method. In this study, for all data fitted with  
322 Surfer, the same gridding methods as Kriging were used with the experimental variograms  
323 fitted with linear component type and no trend removal. The temperature diffuses faster in the  
324 water at the top due to its higher thermal conductivity. The temperature close to the heater is  
325 almost 50°C and due to heat loss, it decreases across the tank to room temperature (20°C).

326 Experimental electrical resistivity value was measured and corrected with temperature  
327 for three testing EDD array levels. In the scatter plots of Figure 4, each point corresponds to a  
328 mean value of a square using an EDD array. Before imbibition, the first level of EDD at the  
329 bottom of the tank had almost the same resistivity. The decreasing resistivity in the middle part  
330 of the tank after imbibition suits the CT saturation decreasing and replacing DNAPL with  
331 water in this part. The points in the boundary of the tank were considered as same as their  
332 neighbor points for interpolation. Our study of temperature and saturation effects has been  
333 done separately for the condition that both factors want to be considered. After correcting the  
334 data for the temperature effect, the impact of saturation changes could be determined. The next  
335 step was pumping CT out from the middle bottom of the tank. Performing the imbibition step

336 was to simulate the thermally enhanced pump and treat technology for soil remediation. The  
337 objective was to monitor how water and CT saturation vary inside the 2D tank using the  
338 electrical resistivity measurements.

### 339 [Validation of the electrical resistivity measurements](#)

340 Before starting the main drainage-imbibition experiment, to validate the performance of  
341 the electrodes, the first experiment was carried out by increasing the CT level in the tank at the  
342 normal room temperature (20°C). In the following, this experiment's data will be compared to  
343 the results obtained from a numerical model. After filling the half bottom of the tank with  
344 GB+CT, the resistivity was measured for 24 hours, then the temperature of the 2D tank was  
345 increased to 30 and 40°C by circulating hot water at a given temperature around the 2D tank to  
346 keep the temperature constant in all 2D tank parts. Compared to heating elements, heating with  
347 this method can result in temperature homogeneity throughout the whole tank.

348 For the main experiment, a laboratory protocol of a multiphase system was defined in  
349 the 2D tank that will be briefly described in the following. The 2D tank was filled with GB and  
350 two different liquids, water as a conductive fluid and CT with low conductivity. At the starting  
351 point, the tank was filled with GB and water layer by layer (Figure 5a). Figure 5b is the tank  
352 filled with GB and water, ready for injecting CT from the 5 points at the bottom of the tank  
353 (Figure 5c). It is necessary to slowly inject CT to have the relatively horizontal CT levels  
354 (Figure 5d). Despite all these considerations, in one case (Figure 5e) when a bump shape CT  
355 surface appears, slight injecting from the sides of the tank can balance the surface of CT in the  
356 tank.

357 We used an open-source modeling tool BERT (Boundless Electrical Resistivity  
358 Tomography) developed by Günther and Rucker (2015) to model this simple drainage  
359 experiment. The possibility of modeling closed geometries as laboratory cells and tanks  
360 encouraged us to use this modeling code. The theory of developing this code based on the

361 finite element method has been expanded from the previous study done by Rucker, Günther  
362 and Spitzer (2006). In the other studies, code was developed for arbitrary electrode shapes  
363 (Rucker and Günther, 2011) and long electrodes (Ronczka, Rucker and Günther, 2015).

364 The 2D tank, by using three series of EDD arrays in different levels, was modeled by  
365 BERT. The fundamental physical theory for electrical resistivity used in BERT software is  
366 based on Ohm's law (Günther et al., 2006). Assuming that the electric fields are conservative  
367 and the magnetic effects are negligible, the mathematical equations can be written as follow

$$\mathbf{J} = \sigma \mathbf{E}; \mathbf{E} = -\nabla V, \quad (8)$$

368 where  $\mathbf{J}$  ( $\text{A.m}^{-2}$ ) is the current density,  $\mathbf{E}$  ( $\text{V.m}^{-1}$ ) is the electric field intensity,  $\sigma$  ( $\text{S.m}^{-1}$ ) is  
369 the electrical conductivity (the reciprocal of resistivity  $\rho$ ), and  $V$  (V) is the electric potential  
370 (primary variable). The initial condition was  $\rho(t=0)=30 \text{ Ohm.m}$  that corresponds to the  
371 electrical resistivity of glass beads saturated by water. Neumann boundary condition (no-  
372 current flow boundary condition) was imposed on all 2D tank borders. The number of  
373 irregularly structured meshes was 1036942 elements.

374 In the other experiment in the 2D tank, increasing CT level is also simulated centimeter  
375 by centimeter from the bottom of the 2D tank up to 18.0 cm from the 2D tank bottom. Before  
376 these steps, we simulate a homogeneous tank filled with only GB and water.

377 After injecting CT, the resistivity values were recorded for these different levels, until  
378 reaching the top of the middle EDD level (17.5 cm). This data allows us to study how  
379 resistivity varies in the experiment and the model according to an increase in CT level.

## 380 Results and discussions

### 381 Correction of data with temperature

382 In remediating polluted sites with the thermal enhanced method, the effect of  
383 temperature on the electrical resistivity should be corrected before studying the effect of  
384 saturation change on geophysical parameters. At the beginning of the experiment, the mean  
385 temperature in the tank was 20°C. The temperature varied between 19.1 and 22.8°C. The  
386 resistivity was corrected with temperature by using the relation proposed by Dakhnov (1962)  
387 and Keller and Frischknecht (1966) to have a geophysical parameter that is only controlled by  
388 saturation.

### 389 Electrical resistivity fields

390 The electrical resistivity variation was used to predict the water/CT saturation change.  
391 The evolution of logarithmic apparent and inverted electrical resistivity (to facilitate the  
392 comparison before and after temperature correction) during the imbibition test is shown in  
393 Figure 6. The objective is to show how temperature changes can impact the calculation of  
394 resistivity. Iravani et al. (2020a) presented how the temperature affects the resistivity value in  
395 a multiphase sample. To study the effect of saturation change due to pumping, it is needed to  
396 deduct the effect of the heating. Figure 6a,b show the log of resistivity before temperature  
397 correction, and Figure 6c,d show the same results with temperature correction. This is the  
398 starting point of our study on the saturation effect on resistivity values in the 2D tank. Figure 6  
399 is cut 10 cm from the left side of the tank to eliminate the influence of the metallic heater on  
400 the resistivity of the medium.

## 401 Validation of the setup configuration and electrical resistivity measurements using 402 BERT modeling

403 In modeling a physical phenomenon, the main constraint for a modeler is dealing with  
404 boundary conditions (Stroud, 2006). The first boundary problems are the Neumann boundary  
405 conditions (Broggini et al., 2017). We need a dipolar current injection to avoid overflow from  
406 the boundaries of the 2D tank (Günther and Rucker, 2013). Using a reference electrode inside  
407 the tank could solve this problem. This reference electrode should be placed slightly away  
408 from the current and potential electrodes inside the tank. The second problem that arises for  
409 Neumann domains is the non-uniqueness of the solution of the partial differential equation due  
410 to a lack of calibration (Günther and Rucker, 2013). We used a calibration electrode to  
411 overcome this problem, which must be placed at the boundaries of the tank. The potential at  
412 this point (electrode) must be zero. The method used in the modeling was moving both  
413 electrodes (reference and calibration electrodes) in the tank and checking if the results  
414 obtained were consistent or not (Günther and Rucker, 2013).

415 To validate our experimental measurements with numerical modeling, we completed  
416 two steps: In the first step, the ratio of geometrical factors  $K$  obtained from the experiment  
417 with water on the 2D tank and model were compared in Figure 7. In both the experiment and  
418 model, the  $K$  varies around 0.45 to 0.5 for the EDD arrays with  $\pm 20\%$  error. We noticed that in  
419 points close to the metal grid on both sides of the tank (e.g., points 23, 24, and 25) the  
420 difference in  $K$  factors obtained from the model and experiment are more significant because,  
421 in the model, the effects of metal grids have not been considered.

422 In Figure 8, after increasing the level from 2 cm (entering the influence zone of EDD  
423 measurements) resistivity was increased both in the experiment and model. Since the influence  
424 zone of all measurements begins at 2.5 cm. In this figure, the model simulation results  
425 properly coincide with the experimental data (Pearson's correlation coefficient,  $R=0.981$ ). This

426 validates the setup configuration and shows that the electrodes measure the resistivity with  
427 good precision. In the transition part at a height of 3 and 4 cm, an overestimation was seen  
428 compared to the experimental resistivity data. This overestimation could be due to the effect of  
429 increasing CT and its direct effect on the resistivity value predicted by the model.

### 430 Phase variation during imbibition

431 During the imbibition period, both amplitude and phase shift of complex resistivity  
432 measured in the middle of the tank were affected by temperature and saturation changes.  
433 Figure 9 shows how phase shift varied with time in the pumping influence zone in the middle  
434 of the tank for two different frequencies ( $f=1.46$  and  $2.92$  Hz). Nine measuring zones (we call  
435 them points in the following) in the same vertical positions were chosen from three levels of  
436 the EDD array in the middle of the tank.

437 Points 12, 15, and 18 are at the top, consisting of the water-saturated zone (GB+water).  
438 The results showed that the phase shift is close to zero in these three points. These results  
439 confirm previous findings on 1D cells and columns for the water-saturated cases (Iravani *et*  
440 *al.*, 2020b). Points 11, 14, 17, and 10, 13, 16 are at the middle and bottom of the tank with an  
441 EDD array, respectively. During the imbibition (pumping process), CT was pumping from the  
442 middle bottom of the tank, and therefore, water replaced CT forming the cone of depression.  
443 As shown in Figure 9, imbibition increased and then decreased phase shift at points 11, 14, and  
444 17 (at the middle of the tank), but it was constant at points 10, 13, and 16 (at the bottom of the  
445 tank). This variation occurred sooner at point 14 than at point 11, which corresponds with our  
446 expectation because imbibition firstly affected the middle points, then the side points because  
447 of the cone of depression. Besides, the phase variations at points 14 and 17 happened at the  
448 same time. Drops in phase shift at the end of imbibition happened later for points 11 and 17  
449 compared to 14 due to the delay of the imbibition effect from the middle of the tank reaching  
450 the sides. After imbibition (dominating water saturation), the phase shift dropped to a value

451 close to zero. An increase in phase was observed in all 3 points in the middle of the tank,  
452 which can show the complex behavior of the spectra and phase due to the instantaneous  
453 change of water/CT saturation. However, we observed a weak response to imbibition tests for  
454 points 10, 13, and 16 situated at the bottom of the tank because they were not influenced by  
455 imbibition.

456 After dominating water in each block of the measurement, the recorded values became  
457 stable and close to zero. Comparing results of the phase change between Figure 9a and Figure  
458 9b shows that small changes in frequency have a large effect on phase shift in layers  
459 containing DNAPL. The higher frequency, the higher the phase shift.

#### 460 Predicting saturation in 2D tank

461 In a previous study, Iravani *et al.* (2020b) found a relation between saturation state and the  
462 amplitude and phase shift of the SIP spectra for CT+water, to have a calibration relationship  
463 for further uses in the 2D tank (current study) and even thereafter in field studies as below  
464 (Iravani *et al.*, 2020b):

$$\sigma_{mixed} = 0.0345\theta_w^{1.8} + 10^{-3}(0.4 - \theta_w)^{5.2} + 10^{-14}(0.6)^{2.34} \quad (9)$$

465  $\sigma_{mixed}$  was obtained from the inverse relationship with the measured resistivity of the  
466 multiphase system in each zone. The only variable in equation (9) is water content ( $\theta_w$ ),  
467 which can be present as water saturation after using this equation ( $S_w = \theta_w / \Phi$ ).

468 Figure 10a,b, and Fig 10c,d show the saturation status and front image of the  
469 multiphase system before and after imbibition in the 2D tank, respectively. In Figure 10c,d, the  
470 strong reduction of DNAPL saturation in the middle of the 2D tank is due to imbibition. The  
471 complex nature of CT that sticks into the 2D tank glass wall surface did not allow image  
472 analysis to obtain the saturation. Therefore, we could not make a quantitative comparison of  
473 the saturation using these images.



474 Figure 10 shows resistivity measurements in different influence zones with  
475 interpolation that can give us the saturation field. In Figure 10c, we expected more saturation  
476 changes before and after the pumping at the left side of the tank compared to its right side. The  
477 heating from the left side has a direct effect on the viscosity of CT and consequently, the  
478 pumping rate, but the DNAPL/water interface is not horizontal and we could not quantify and  
479 make this assumption. As observed in Figure 6d and Figure 10c, the effect of imbibition seems  
480 to be well observed particularly in both sides compared to the middle.

481 The CT saturation was not exactly 100% even before starting imbibition because some  
482 percentage of water was captured in the pore spaces before injecting CT. It seems the Archie  
483 model does not have enough precision (the effect of surface conductivity should not be  
484 neglected) in very high resistivity (high CT saturation) and that monitoring in a small 2D tank  
485 does not allow us to capture the cone of depression with high precision for imbibition.

#### 486 [Effect of temperature and saturation on Cole-Cole parameters](#)

487 In the non-isothermal condition before starting imbibition when the bottom half of the  
488 tank was filled with GB+CT, the complex resistivity was measured in the frequency domain  
489 (e.g., under electrical impedance conditions) before and after heating. The tank was heated  
490 from the left side by a heater and heat was dispersed from the left side of the tank to the right.  
491 The most influenced part is close to the heater. There the temperature changed from 20 to  
492 50°C, and that change affects two EDD measurements at the far-left side of the tank (No. 1  
493 and 4). Figure 11 shows how the four Pelton parameters vary at 20 and 50°C. The  
494 experimental data were fitted to the Pelton model by using a Matlab code by Mainault *et al.*  
495 (2017). The fitting curves of the experimental data and model are presented in Figure 12.

496 We have already studied how these parameters vary with temperature in cells and  
497 columns (Iravani *et al.*, 2020a). Studying these parameters in the 2D tank showed that  $\rho_0$  and

498  $\log(\tau)$  were decreasing with temperature increases. Raising the temperature from 20 to 50°C  
499 slightly increased  $c$  but both  $m$  and  $c$  were so close to 1 that it can be considered as a constant  
500 value. The fact that  $c$  is close to 1 means that the SIP response obeys a Debye model, and the  
501 fact that  $m$  is close to 1 means that the medium is highly chargeable because of poor dispersion  
502 of the spectra. These variations in results were the same for both measurements (1 and 4). Our  
503 findings on how the four parameters changed in the 2D tank confirm the previous findings on  
504 cells and columns with this difference:  $m$  was 0.89 and in the 2D tank for both measurements  
505 was almost 1.

## 506 Conclusions

507 The main goal of this study was to move one step closer to execute the usage of electro-  
508 geophysical methods to monitor the saturation changes in soils contaminated by a DNAPL  
509 (like CT) under non-isothermal conditions. In particular, applications of the SIP method in  
510 contaminated porous media were examined experimentally in the laboratory by using a 2D  
511 sample tank. Glass beads of 1 mm diameter were chosen because of similar physical properties  
512 to field soil. This allows to model as much as possible actual field conditions in the laboratory.

513 After preparing the non-isothermal condition by heating from the left side of the tank and  
514 correcting the temperature effect, we studied how the electrical complex resistivity varies  
515 during imbibition. Changes in the electrical complex resistivity magnitude were measured and  
516 the saturation field was obtained from the resistivity data. From the electrical resistivity  
517 measurements, we predicted the changes of the saturation field before and after imbibition  
518 accordingly. However, the proposed electrical resistivity monitoring did not produce the cone  
519 of depression during imbibition with high precision. This may be related to CT's very high  
520 resistivity and the small laboratory setup. The phase changes in 9 points in the middle of the  
521 tank in all three levels showed that the phase significantly decreases after increasing water  
522 saturation (imbibition period).

523 It is concluded that the temperature (5 to 7%) and saturation change due to replacing CT  
524 with water affects measured electrical complex resistivity. The effect of saturation change is  
525 much more considerable compared to the temperature. In the coupling of temperature and  
526 saturation variation after correcting resistivity with temperature (with a linear relation), the  
527 saturation effect will be the only variable in the real case with remediation surveys under the  
528 thermal-enhanced technique.

529 The effect of saturation change by injecting CT from the bottom of the tank was  
530 evaluated by BERT as a numerical modeling tool. The results show that the measurements  
531 with EDD arrays have been properly fitted by the BERT model. This validates our setup  
532 configuration and confirms that our electrodes functioned properly. The goal of our study was  
533 not to present comprehensive mechanistic modeling of the results but to present the  
534 experiment and the results that show the effect of heating and pumping on the SIP response,  
535 and its interest for field measurements. Developing a mechanistic model is a step beyond, the  
536 subject of future research.

537 The reported results showed that the proposed generalized Archie's law from the  
538 previous study could predict the saturation. However, during pumping at the bottom of the  
539 tank, the proposed coefficient did not perfectly reflect the saturation change. Finding the  
540 proper coefficients of generalized Archie's law can lead to precise saturation estimation in  
541 both high and low resistivity. These results at the bottom level during imbibition could be due  
542 to placing the current electrodes in the part that is saturated with CT. Our previous finding in  
543 1D cells supports also the idea that in a case where the current electrodes are located in a  
544 saturated DNAPL part, SIP reports very high resistivity although the potential electrodes are  
545 still placed in the water-saturated part.

546 How Cole-Cole parameters change before and after heating were evaluated for 20 and  
547 50°C before and after heating. The results of this study show that Cole-Cole parameter  
548 variations are in accordance with our previous findings.

549 We believe that the most outstanding part of our findings is the development of  
550 knowledge on how to monitor imbibition processes where both temperature and saturation  
551 change together in a 2D system. Validating our results in electro-geophysical field studies  
552 would advance their reliability in various environmental conditions. Our findings might be  
553 used for soils with similar physical properties.

## 554 **Acknowledgments**

555 This study was performed as part of the Bioxyval project. The authors would like to  
556 thank ADEME (French Environment and Energy Management Agency) for co-funding the  
557 project under the “AMI” program. We gratefully acknowledge the financial support provided  
558 to the PIVOTS project by the “Région Centre – Val de Loire” and the European Regional  
559 Development Fund.

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## 793 **FIGURE LEGENDS**

794 **Figure 1** Schematic layout of the a) front, b) top and, c) back of the 2D tank with the  
795 description of each element. In the front view of the tank, a double glazed transparent glass is  
796 used as a wall to better control the temperature and imaging purpose. Isothermal system  
797 includes a system of heating all around the tank using hot water. A stainless-steel heating  
798 element was inserted inside the left-side of the tank to produce the non-isothermal condition.  
799 In sub-figure c) the red square showed an EDD measurement. There are 27 EDD  
800 measurements in three different levels.

801 **Figure 2** Equatorial dipole-dipole arrays from the front side of the tank. 10 current (metal)  
802 electrodes and 10 potential (non-polarized) electrodes in each level can record 9 EDD  
803 measurements. In three levels of measurements, 27 measurements can be recorded. Using  
804 other arrays (e.g., Wenner Beta) is also possible between two levels.

805 **Figure 3** Linear regression to find the  $\alpha$  values for a) GB+water in the top level and b)  
806 GB+CT for the bottom level of EDD array. The obtained  $\alpha$  values for GB+water and GB+CT  
807 are in accordance with the results of the previous study on 1D columns (Iravani et al., 2020a).

808 **Figure 4** Back view of the temperature field in the tank under non-isothermal conditions a)  
809 before, and b) after imbibition (the plus (+) signs are the positions of the thermocouples and  
810 red dot is the pumping point at the middle bottom of the tank). A significant temperature (54  
811 and 18 °C) difference between the right and the left side of the tank is due to using a heater at  
812 the right side of the tank (in the back view).

813 **Figure 5** Different steps of experimenting on the 2D tank. a) filling the tank with GB and  
814 water, b) tank packed with GB and fully saturated by water, c) injecting CT from 5 points at  
815 the bottom of the tank (for the places of injecting points, please see Figure 1a), d) increasing  
816 step by step the level of the CT in the tank, e) possible bump shape of the CT surface – the flat  
817 interface is ideal, f) almost half of the tank filled with GB+CT. This stage is the starting point  
818 of the imbibition experiment.

819 **Figure 6** Log of the resistivity field in the tank a) before imbibition, b) after imbibition  
820 without temperature correction, and c) before and d) after imbibition with temperature  
821 correction, e) inverted log resistivity before temperature correction, and f) inverted log  
822 resistivity after temperature correction (the circle (●) and blue arrow signs are respectively the  
823 positions of the EDD measurements and drainage points).

824 **Figure 7** Experimental and model ratio of K factor for 27 measurements of electrical  
825 resistivity with EDD array. Point values closer to 1 show a better model prediction of the  
826 experimental data. Points far from the walls have better results because of the metallic grid  
827 used in the side walls.

828 **Figure 8** Variation of resistivity as a function of CT height for EDD array at the bottom level  
829 of the tank. These are apparent resistivity obtained from the average values of the 9  
830 measurements at the bottom level of the 2D tank (measurements No: 1, 4, 7, 10, 13, 16, 19, 22,  
831 and 25; see Figure 2).

832 **Figure 9** Variation of phase shift during imbibition period at the middle of the tank in 9 points  
833 (12, 15, and 18 at the top level, 11, 14, and 17 at the middle level, and 10, 13, and 16 at the  
834 bottom level) for the frequencies of a) 1.46 Hz and b) 2.92 Hz.

835 **Figure 10** a) The measured CT saturation field before imbibition, b) front image of the 2D  
836 tank before imbibition, c) the measured CT saturation field after imbibition, and d) front image  
837 of the 2D tank after imbibition. The black lines in “a” and “c” are the counters between two  
838 areas (GB+water and GB+CT).

839 **Figure 11** Effect of temperature on Cole-Cole parameters (20 and 50°C) close to the heater.  
840 As it was shown in Figure 5, just points close to the heater have recorded the temperature  
841 around 50 °C.

842 **Figure 12** Fitting curves of experimental data and model for a) point 1 at 20°C, b) point 1 at  
843 50°C, c) point 4 at 20°C, and d) point 4 at 50°C. For more information about choosing the  
844 presented points, see Figure 11 description).

845



846

### **Data Availability Statements**

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848 The datasets generated and analyzed during the current study are available from the  
849 corresponding author on reasonable request.

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### **Declaration of interests**

852

853  The authors declare that they have no known competing financial interests or personal  
854 relationships that could have appeared to influence the work reported in this paper.

855

856 The authors declare the following financial interests/personal relationships which may be  
857 considered as potential competing interests:

858

859