CONTRIBUTION OF CAPACITANCE PROBES FOR NONDESTRUCTIVE INSPECTION OF EXTERNAL POST-TENSIONED DUCTS

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Abstract: In bridges, external post-tension habitually comes as cables placed in ducts for which the residual internal space is (imperfectly) filled with a fluid cement grout. Detecting the problems of injection is not practicable visually from the outside, and no effective auscultation tools were found yet. A recent laboratory experiment established that capacitance probes can be employed, but the main difficulty is to provide a correct interpretation of the measurements in terms of deterioration of the coating, along with the occurrence of water or grout voids. In order to understand if the presence of the cable itself can disturb the diagnosis in such proportions that any inspection is destined to failure, the subject was tackled here from a numerical point of view. It is shown that the capacitance probe is sensitive to the location of the cable, but that it is still possible to distinguish typical defects present at low depth. This result is confirmed, from a qualitative point of view, by tests performed with an actual probe.

Introduction: A lot of bridges and tunnels include "external" post-tension (so called since it is not in the concrete material, hence potentially accessible for measurement), either originally or a after reinforcement of structure. The cables are generally placed in High Density Poly-Ethylene (HDPE) ducts, where the residual space is filled under high pressure with a cement grout intended to prevent corrosion. This protection being imperfect, cable breaking occurs in non-protected zones because of the presence of a "white paste" (not hardened grout with a high water content) or grout voids.

The detection of such defects inside an opaque duct is unachievable visually from the outside. Furthermore, already existing procedures (Derobert *et al*., 2002) often involve the damaging creation of apertures on the duct envelopes to look inside or introduce an endoscope. Another approach employing gamma-rays radiography is cumbersome and expensive, acoustic methods are not precise enough, *etc*. In these conditions, there are few available *modus operandi*, and the need for a reliable diagnosis urgently requires the development of effective investigation tools to prevent unnecessary strengthening and repair, or even replacement (Cavell *et al*, 2001).

Electromagnetic methods are suited for many purposes, amid, capacitive measurement is implemented on a regular basis for a quantitative estimation of the water content of soil (Fares and Alva, 2002), cement (Smith *et al*., 2002), or agricultural products (Nelson, 1992). This technique is also appropriate to assess the porosity of volcanic rocks (Rust *et al*., 1999), voids fraction in multi-phase flows (Kendoush and Sarkis, 1996), *etc*. Further, capacitance detectors are employed for the qualitative differentiation of materials like clear wood from knots and distorted grain (Steele and Kumar, 1996), to characterize biologic cells (Asami, 2002), to sound snow packs in avalanche forecast (Louge *et al*., 1998), and to detect buried plastic landmines (Mamishev, 1999). Capacitor properties provide non destructive tools (Matiss, 1999) at micro-scale as well, for instance to inspect electronics products (Ruprecht *et al*., 2003) or control their processing integrity (Jeandupeux *et al*., 2002).

In the same manner, the auscultation of external post-tensioned ducts with a capacitance probe was found to be workable during laboratory experiments (Dupas *et al*., 2001). The tests utilized long transparent proof bodies, containing a steel cable, and acting as duct pieces. Holes allowed the introduction of water, sand or air, and the emptying. Two rectangular electrodes applied on the outer surface of the samples were moved around and along the proof axis, repeatedly. An alternating current being applied between the plates, the system constituted some sort of capacitor coupled into a high frequency resonant circuit. The resonant frequency shift is indicative of the nature of the materials inside the duct.

However, without knowledge of the factors susceptible of influencing the measurements, operators experience and shrewdness are necessary for interpreting the capacitance data. Moreover, previous sampling and calibrating phases are necessary to have a chance for relating measured and searched information. Indeed, the case of post-tensioned ducts is complex, since they appear as an heterogeneous mixing of conductors and dielectrics, and as internal geometry interferes in an undefined manner. Accordingly, it seems judicious to study first the influence of each contribution independently, starting from the most important processes, or at least (those sought to be) governing features.

Actually, the first question we have to answer is: does the presence of the steel cable influences the measurement in such proportions that any inspection for detecting inclusions is destined to failure ? The problem was tackled here from an electrostatic point of view, and a model of post-tensioned duct was used for a numerical evaluation of its dielectric capacitance by solving the corresponding set of equations with finite elements. After setting up the configuration in the first part of this paper, several situations are studied in a second section for a sensitivity study in typical capacitors where the nature of the constituents as well as the location of the post-tensioned cable both vary. At last, an example of measurement obtained in the laboratory with a capacitance probe is described as well as the corresponding simulation.

Setting up: A sketch of external post-tension duct containing a seven-tendons steel cable at the bottom is shown on Figure-1. Here, the volume of the HDPE envelope is imperfectly filled of cement grout, with an air pocket and a water saturated material layer (*i.e.*, not hardened paste), as may occur frequently.

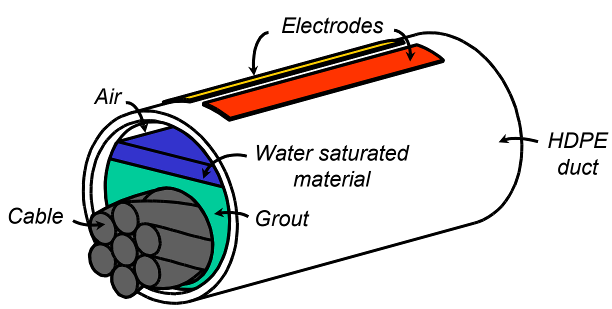

Figure-1: Example of post-tension duct having a steel cable and various materials inside, with the sensing and driven electrodes outside.

The electrodes of the probe are slid on the duct, in order to allow measurements longitudinally, referred hereafter as the z coordinate, and transversely by rotation θ of around the z-axis. For the moment, displacements of the sensor are carried out manually, but in a short term a completely autonomous (motorized) probe is planned.

Regarding the different constituents of the system, some (steel, for instance) are excellent electrical conductors, other are insulators (HDPE), and between the extremes, most materials are more or less conductors. Indeed, their effective dielectric constant is highly sensitive to water content, since the relative dielectric constant of water is several orders of magnitude higher.

The investigation frequency (and alternating electric field) can be properly selected, based on information about the materials electromagnetic properties thoroughly measured individually over a broad range, in particular for the cement grout (Al-Qadi *et al*., 1995; Al-Qadi *et al*., 1997). But in the end, the frequency dependence of the mix (Priou, 1992) cannot be only attributed to the intrinsic properties of each material (one of the reasons being the interfacial polarization mechanisms). However this intricate point is out of the scope of the present work, so the dielectric constants of pure (not combined) constituents are set to fixed values for conducting the preliminary computations.

The configuration of a "conventional" parallel plate capacitor would require a contact with the material under test from two opposite sides. The variation here is that the electrodes of the sensor are placed next to one another (see on Figure-2), so as to provide a sufficient penetration depth of the electric field between sensing and driven devices, and to allow measurement in situations where accessibility is difficult (Diefenderfer *et al*., 1998).
Considering the shape of the electrodes, it was shown (Xu *et al*., 1999) that the sensing range of similar systems narrows slightly when their length (along the main line, parallel to the z-axis) decreases to less than 150 mm, whereas the reduction of the corresponding capacitance value makes it more difficult to measure. Accordingly, a geometry was chosen after performing several experiments, and for the sensitivity analysis we used rectangular sensing items of length 150 mm. The width of the electrodes was taken as θ_e=20° arc following the roundness of the duct, with a $\Delta\theta_e$=10° separation space between them.

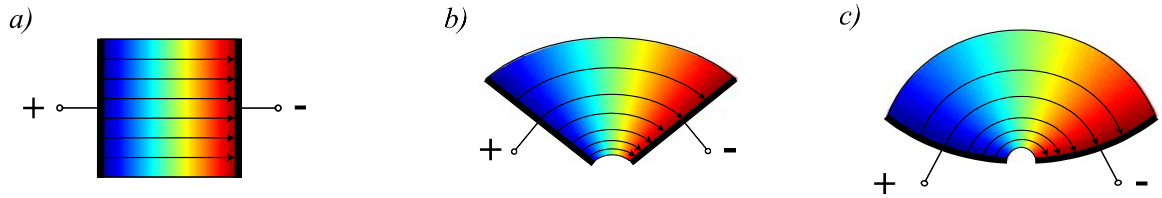

Figure-2: The configuration of the sensor can be seen as the result of two processes: gradually open the angle between the electrodes of a parallel plate capacitor from situation a) to c), then add a slight curvature to adapt their shape to the roundness of the duct (c).

We handled here a three-dimensional electrostatics model of the system based on linear homogeneous isotropic materials, defining as many independent sub-domains. For the numerical resolution of the problem using finite elements we implemented the FEMLAB 2.3 package (COMSOL AB., http://www.comsol.com). This software was running with the MATLAB 6.5 interface (The Mathworks Inc., http://www.mathworks.com).
Basically, modeling of the electric field is carried out using the electric potential V, calculated from the Laplace equation. Appropriate boundary conditions are straightforward: the electrodes are equipotential surfaces, and the remainder is insulated electrically. The capacitance of the system is achieved by means of a calculation of the electrostatic energy.
Actually, spaces on both sides of the electrodes intervene, so that the resulting layout does not constitute a single capacitor but two capacitors in parallel, which corresponds to type "external electrodes without radial screen" in the classification of Yang (1997). The first one (capacitance C_i) being formed by the duct (capacitance C_d) plus the material inside (capacitance C_m), in series, and the second (C_e) by the surrounding environment (principally air and plexiglas making up the probe), and the total capacitance (C_t) is the sum (see Figure-3).

$$C_t = C_e + C_i = C_e + \frac{1}{\frac{1}{C_d} + \frac{1}{C_m}} = C_e + \frac{C_d\, C_m}{C_d + C_m}$$

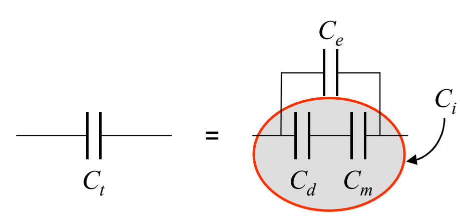

Figure-3: Simplified model of the system and the associated representation.

A relationship between the measured capacitances and corresponding resonant frequency shifts can be obtained, knowing the inductance of the electronic circuit. However, for the sake of convenience, we'll only deal with the capacitance of the inside volume in the rest of the paper. In practice, some precautions must be taken in order to prevent the so-called "hands effect" or interference of external electrical fields: metallic screen to shield the electrodes from external fields (Yang *et al*., 1995), radial earthed screens between the plates to decrease the inter-electrode capacitance external to the duct (Yang and York, 1999), *etc*.

Results and discussion: The first considered configuration, to evaluate the influence of the location of the cable (Figure-4), is that of a duct perfectly filled with cement grout (no void or "white paste") where the whole steel cable is moved from the center towards the edge (at the bottom). The electrodes are rotated around the z-axis, starting from the top (θ_e=0°), while passing by bottom (θ_e=180°), with a return to the initial point.

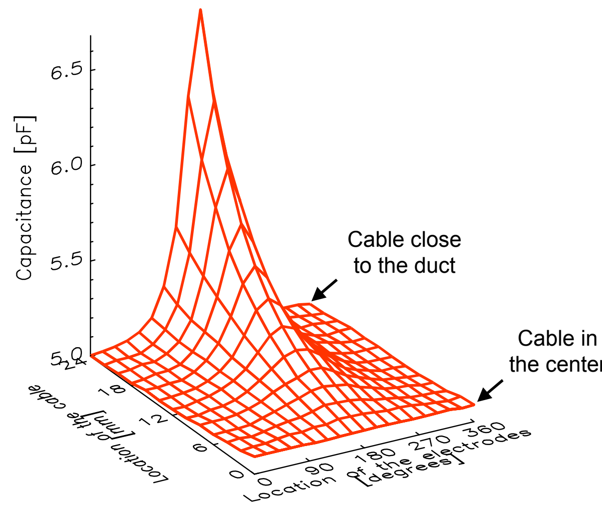

Figure-4: Influence of the location of the cable on the resulting capacitance of the system. The axes indicate the angular location of the sensor θ_e*, and that of the cable in the duct.*

When the cable is in the center of the duct, the capacitance obviously remains the same, whatever the location of the electrodes. A cable shift generates a surge of the capacitance value in the corresponding half part of the duct: the increase approximately affects modeled capacitances in the range of $\theta_e \in [90°, 270°]$. The auscultation depth being roughly 20 mm in this construction, it turns out that the cable acts as a screen when it approaches the edge. Therefore, phenomena occurring behind may be invisible in certain configurations but the rest of the duct should be properly sensed.

To study the effect of air and water layers, consider one of the curves taken from the situation already examined, with the HDPE duct, the steel cable close to the bottom of the duct, and the grout (Figure-5). On both sides of the graphs (θ_e<90° or θ_e>270°), the capacitance is about 5 pF, and as long as it remains in the sensed area, the influence of the cable dominates. The maximal value is obtained when the steel cable is near the outer surface of the duct (having its center located at 24 mm), in the vicinity of the electrodes (at an angle of about 180°). When a horizontal air layer is formed above the grout, the capacitance drops off drastically (something like a –50 % fall): this sudden decrease of the values is undoubtedly indicative of the presence of air in the volume. In the last case, we took into account the presence of material simulating "white paste", between the grout and air regions. As the electrodes approach this layer with a high water content, there is an increase of the capacitance compared to the previous arrangement. The phenomena in particular affects the response of the device when it is located exactly above the considered zone, with little bumps on each sides of that are due to the cable.
As a result, we can suspect that a capacitance value lower than that of the configuration where there is only grout and a cable in the middle of the duct, is a distinguishing attribute of grout voids. However, the signature of the "white paste", generating a larger capacitance, is similar to that of the cable itself, but generally with a smaller extent. Accordingly, and without any indications about the precise location of the cable, the interpretation of the measurements may be confusing.

Fortunately, the course of the cables in the duct between two spacers is well known, and the formed undulation is rather regular, which is not true for randomly occurring flaws with a much smaller size. Furthermore, because of the inclination of the ducts (Leroy *et al*., 2000), occurrence of grout voids and “white paste” takes place about the higher part, in general. Therefore, this *a priori* information will help discriminating between the cable and zones with a high moisture content, by considering capacitance changes as a function of the location along the duct axis. Hence, smooth variations will be related to the cable, whereas more chaotic changes correspond to defects with a smaller extent.

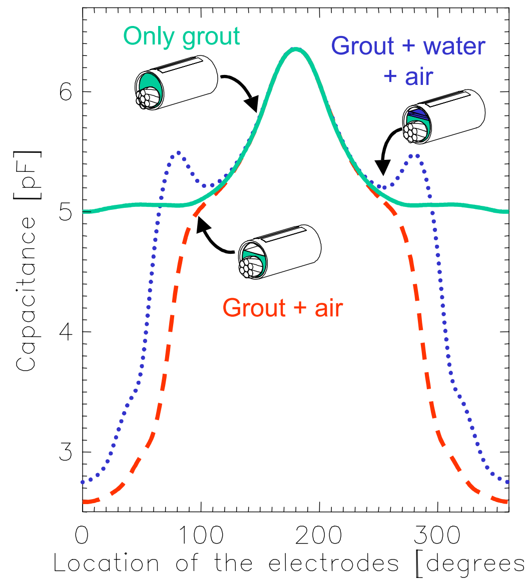

Figure-5: Capacitance calculated for three configurations: cable + grout only (solid line), cable + air (dashed line), cable + water + air (dotted line).

The flaws considered in the previous section were very extended horizontally, but what would happen for the <u>detection of inclusions</u> with dimensions much smaller than that of the electrodes (Figure-6a) ? Here we assume that a grout void (*i.e.*, bubble), or a water saturated material region (for simulating “white paste”) are formed in the grout, in the upper part of the duct (for θ_b=0°), and at an abscissa z_b=0, while the steel cable is in the center. For several angular position θ_e all around (between 0° and 180°, the other side is symmetrical), the electrodes are moved along the z-axis.

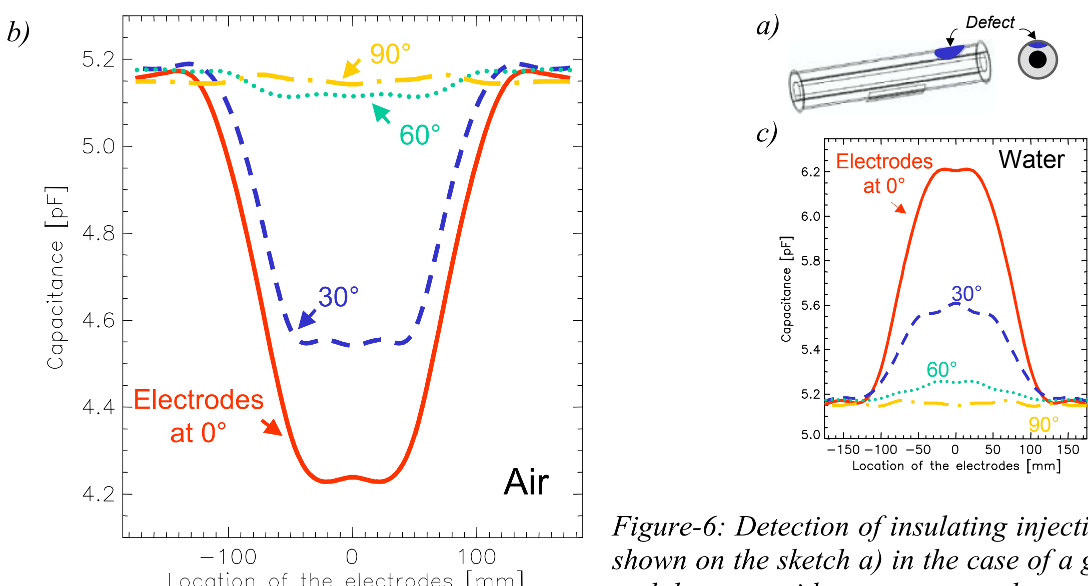

Figure-6: Detection of insulating injection defects (as shown on the sketch a) in the case of a grout void (b), and the same with water saturated material (c).

As long as the capacitive sensor is "far" from the inclusion, either longitudinally ($|z_e|$ larger than about 180 mm) or angularly (from $\theta_e \approx 60°$) there is no nearly sensitivity. However, when the electrodes are near the defect (*i.e.*, when it is located just below the electrodes, on the other side of the HDPE duct) the response is noticeable. For a grout void, the decrease of capacitance value is smaller than in the case of the horizontal air layer because of a smaller extent. A comparable behavior is observed for water, but this time with an increase.

It seems that, with the geometry of the electrodes used, the discrimination of the two inclusion types is possible. The localization is fine, and a rough estimation of the dimension is also allowed. A more detailed sensitivity study should bring soon additional information about the most appropriate electrodes shape as a function of the minimal size of the imperfections to be detected.

For laboratory measurements, a sample was especially prepared with a HDPE duct, hardened grout at the bottom (no steel cable), an inclined layer of not hardened grout, and air at the top (see Figure-7).

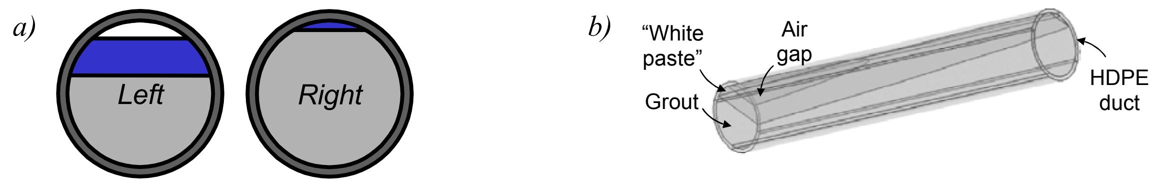

Figure-7: Sample prepared for capacitance measurements: a) distribution of materials inside the HDPE duct, with grout at the bottom, an inclined layer of "white paste" above, and an air gap on the top (from the left and right sides); b) corresponding model used for numerical study.

In the actual probe, electrodes are 165 mm long, with a 10° arc width, and a 10° separation, so we considered the same geometry for the numerical calculations below. Furthermore, as this version of the probe implemented an automatic compensation (including different calibrations and a readjustment), a point-to-point comparison is not possible. Note that such data processing (software and associated electronics) will be changed in the next release of the sensor (for getting absolute values), but we are restricted here to have a qualitative comparison only.

The sensor was rotated around the proof for characterizing different cross-sections: above the air gap and "white paste" overlaying the grout on the left side (Figure-8a), and only "white paste" plus grout on the right side of the sample (Figure-8b). Small icons on each graph present the measured resonant frequency shift, for information. Data are somewhat disturbed, but the behavior seems to be comparable for the model and the experimentation.

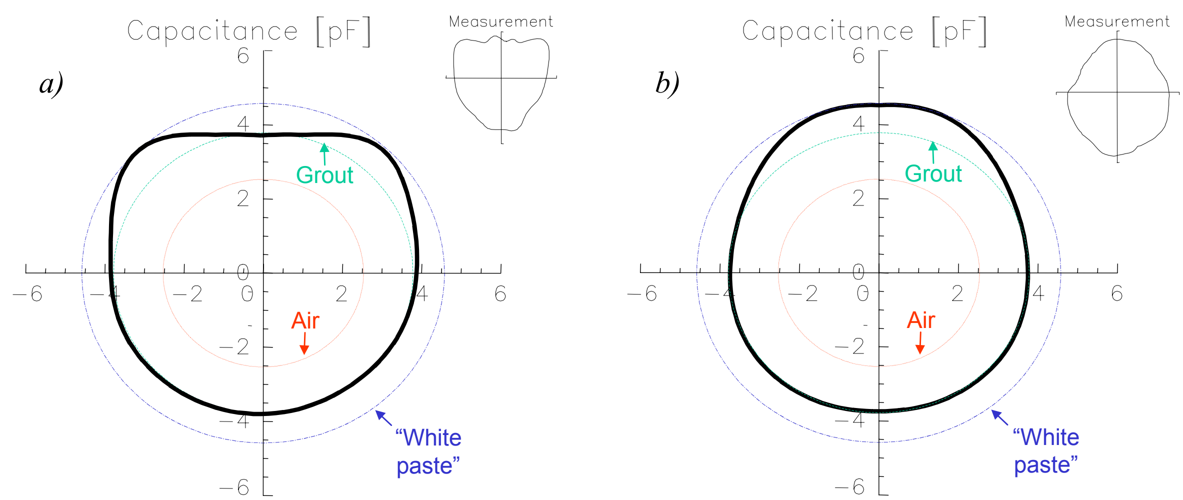

Figure-8: Polar plots of computed capacitance values for cross-sectional areas located on the left (a) and right (b) sides of the proof body (thick line). The circles correspond ducts only filled of air (dashed line), grout (dotted line) or "white paste" (dotted-dashed line). Icons on the right of the graphs display the corresponding resonant frequency shift, for a qualitative comparison.

Straightforwardly, for a duct completely filled with either air, grout or "white paste", the capacitance measured when rotating the probe would remain the same (concentric circles on the graphs). Moreover, as already shown, occurrence in the sampled volume of a substance having a high or a low permittivity should increase or decrease the corresponding capacitance values, respectively.

Regarding the left cross-section (Figure-8a), the little bumps on both sides of the plot (at about +/- 45°) can be attributed to the "white paste" layer, and the depression at the top (0°) is related to air (with a decrease of the capacitance value, compared to the adjacent points). On the right cross-section (Figure-8b), there is no more gap, and the presence of the high moisture content material is noticeable as the plot follows the "white paste" curve in the range of approximately +/- 20°. In the rest of the plot, the capacitance is close to the only-grout case.

Conclusions: Evaluating the actual state of civil engineering infrastructures is a priority for their administrators, knowing the high cost of the construction compared to that of maintenance. For post-tensioned concrete bridges with internally grouted tendons, there was a lack of tools able of revealing the presence of grout voids and high moisture content regions resulting in most of the common pathologies. In this context, the capacitance method appears as a powerful non-destructive approach, and the device proved efficient to find grout injection defects; Information about an elementary tendon failure or substantial cable corrosion analysis should be also potentially achievable in the same way.

Indeed, in spite of a small penetration depth, this method can be fully exploited in complex situations involving a combination of conductive and resistive materials, where no other system is usable. Furthermore, it is possible to adjust the investigation volume, by varying both the arrangement and geometry of the electrodes. This point is still subject to researches, in particular to prevent erroneous measurements due to fringing effects, or to improve the axial evenness by adding appropriate guard rings (Yang *et al*., 1999).

The applications of this atypical technique have remained marginal in the field of civil engineering, because of the difficulties for interpreting the measurements. Furthermore, the behavior of the sensor may be disturbed by a variety of factors, for instance the presence of thin air layers inside the duct (because of grout shrinking when drying), frequency dispersion, phenomenon of interfacial polarization of the electrodes, imperfect contacts with the duct envelope, *etc*. These points are now being considered from a physical modeling point of view, and we can expect technical advances (*via* the implementation of array sensors, as an example) as well as an evolution of the data-processing.

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