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Comprehensive Understanding of Electrical Conductivity Measurements of Gas Diffusion Media of PEM Fuel Cells

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ABSTRACT

Knowledge of the electrical resistivity of components in polymer electrolyte membrane (PEM) fuel cells is important. Generally, the electrical properties are dependent on the solid material of which the layers are composed as well as their physical structure (e.g. fiber alignment and geometry and porosity). Further, the electrical resistance between the layers affects the overall electrical properties of the cell. In this work, a comprehensive overview of techniques available to measure the electrical properties of the gas diffusion media of PEM fuel cells is given. Although the discussion covers the measurement of both in- and through- plane properties, attention is particularly given to the through-plane properties. Problems associated with measuring the electrical properties in the through-plane direction of highly porous and thin materials are hence discussed. Suggested solutions are finally given. The discussion is carried forward using measured properties.

Keywords: Electrical conductivity, Through-plane, PEM fuel cells, Gas diffusion media

1. Introduction

Knowledge of the electrical resistivity of the components of polymer electrolyte membrane (PEM) fuel cells is important for understanding the losses associated with electron transfer. In general, the flow path of the electrons depends on the resistivity of the solid material of which the cell layers are composed as well as the electrical resistance between the respective layers.

Generally speaking, the electrical conductivity of porous structures is expressed in terms of an effective property, which takes into account the volume fraction of the solid material of the layer. For the purpose of PEM fuel cells, the effective electrical conductivity is often expressed in terms of the Bruggeman approximation as follows [1]:

$$\sigma_s^{eff} = \sigma_s(\varepsilon_s)^m \qquad (1)$$

where σ_s^{eff} and σ_s are the effective electrical conductivity of the layer and the bulk electrical conductivity of the solid material making up the layer, respectively, ε_s is the solid fraction and m is Bruggeman factor with a typical value of 1.5. The non-linear dependency of the effective electrical conductivity on the solid fraction implies that electrical resistance through the material must be taken into consideration. This internal resistance can arise due to the distribution of the solid material and hence the inhomogeneity of the surface contact area between the particles. Although Equation (1) is the most widely used in the literature, various other approximations are also used (see [2, 3]).

Although the mathematical derivation, on which these correlations are based, is different, they all have two major drawbacks. First, it is often difficult to obtain the

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conductivity of the base material and second, the structure effects can either be under or over estimated. Hence, in recent years there has been a growing interest to experimentally estimate the electrical parameters of the cell components, such as conductivity and contact resistance. This type of measurement is often carried out with the use of a variant of the four-probe technique.

Williams et al. [4] used this technique to measure the in-plane electrical resistivity of SGL carbon paper and its dependency on the structure of the material. Nitta et al. [5] measured the effect of compression on the through-plane and in-plane effective electrical conductivity of SGL 10-BA using gold coated electrodes. To decrease the contact resistance between the layers under investigation and the electrodes, the GDL under investigation was sputtered with silver particles in [5]. The effect of orientation in the in-plane direction and the effect of PTFE content on the interfacial resistance of SGL series 10 carbon paper were reported in [6]. A micro-wire was used as the voltage contact (probe) for measuring through-plane conductivity of thin carbon paper in [7, 8].

Analyzing the data collected from literature, it is observed that there is no consensus in measurement apparatus for measuring the through-plane conductivity. This is mainly attributed to the difficulties associated with measuring the voltage drop over the thickness of a porous, thin layer. In this work, we investigate three techniques with which the through-plane conductivity can be measured. Problems associated with each technique are discussed. Based on experimental data, recommendations are made.

2. In-plane electrical conductivity

2.1 Description of apparatus

The apparatus used is based on the principles of the four-probe technique. With this method, current is supplied on two ends of the sample and the voltage drop between these points is measured as illustrated in Fig. 1.

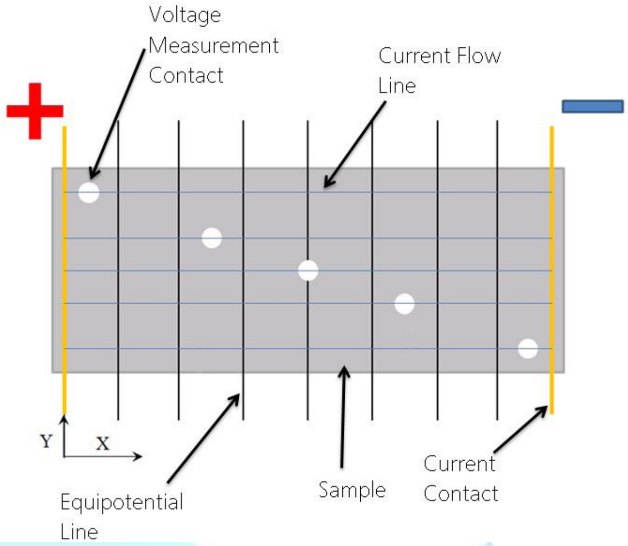

Figure 1: Illustration of the 4-point measurement technique showing the equipotential lines corresponding to the setup with a current supply over the entire sample edge

In general, it can be said that the resistivity of the material under investigation can be obtained using Ohm's law as follows:

$$\rho = \frac{RA}{L} \tag{2}$$

where ρ is the electrical resistivity of the sample (Ω.m), $R = \frac{\Delta V}{I}$ is the resistance due to the potential drop in (Ω), A is the cross-sectional area of the sample ($A = wt$) in (m^2), w is the width of sample in (m), t is the thickness of the sample in (m) and L is the distance between the two voltage probes in (m). In this case, the cross-sectional area considered is equal to the width of the sample times its thickness. Due to compression, the thickness of the sample changes and hence it should be measured at each compression rate. For this purpose, proximity sensors are used to measure the compression rate of the sample at each compression pressure.

In this apparatus, the current is supplied on the entire edge/boundary of the sample as illustrated in Fig. 1. A total of five voltage probes are used; hence, four measurement points of the voltage drop are obtained per experimental point and the obtained resistivity of the sample is hence an average of four points. The two electrodes are composed of a gold coated copper material to prevent an oxidized layer from forming on their surface. The electrodes are electrically insulated from the carrier plate by insulating strips. The contact probes have a flat head pin.

The samples used in this measurement have an area of 3 X 5 cm^2. To validate the measurement technique and the apparatus, the electrical resistivity of a reference material (copper) was measured and validated.

2.3 Results

The dependence of the in-plane electrical resistivity of TORAY-TPGH 120 and SGL 10 BA on compression pressure is given in Fig. 2. From this figure, it can be seen that the conductivity of the materials in the in-plane direction is high.

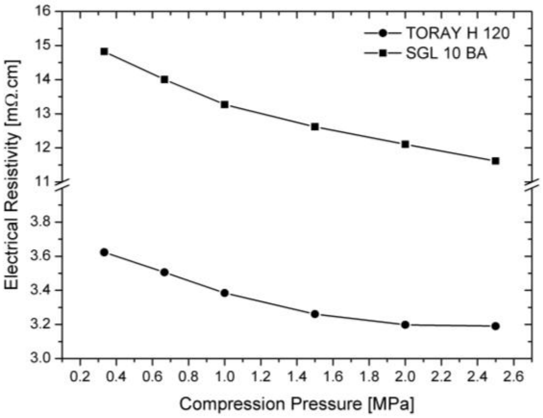

Figure 2: In-plane electrical resistivity of TORAY H 120 and SGL 10 BA for various compression pressures

3. Through-plane electrical conductivity

3.1 Gold-coated electrodes

With the use of such an electrode, the voltage is sensed on the gold coated electrodes as shown in Fig. 3. The voltage drop between the two electrodes can then be used to calculate the sample's resistance according to:

$$R = \frac{\Delta U}{I} \qquad (3)$$

where ΔU is the voltage drop measured between the two electrodes in V and I is the current passed through the sample in A.

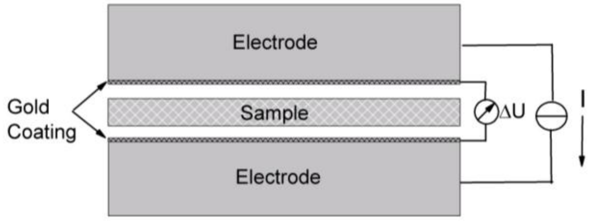

Figure 3: Gold-coated electrodes setup

Upon measuring the resistance through the sample, its resistivity can then be calculated according to Equation (2). However, it should be pointed out here that in this case, the cross-section area, A, is equal to the width of the sample times its length ($A = w.l$) and the length of the conduction, L, is equal to the compressed thickness of the sample. The conductivity can then be calculated as the reciprocal of the resistivity. The sample used in this measurement is circular with a diameter of 20 mm.

3.2 Gold pin probes

In order to eliminate the effect of contact resistance between the electrode and the sample, a contact pin is used as the voltage probe as shown in Figure 4. With this setup, the voltage drop is sensed directly on the sample; thus, the resistance measured is that of the material. The main problem associated with this technique is the distortion of the iso-potential lines within a thin sample; hence underestimating its resistance.

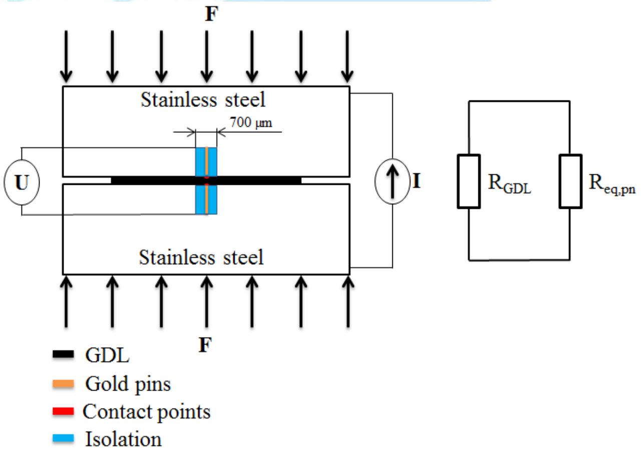

Figure 4: Gold pin electrode setup

3.3 Gold wire probes

The idea of using gold wires as sensing probes of the voltage drop within the sample stems again from the desire to directly sense the voltage on the surface of the sample. Hence, contact resistance between the electrode and the sample is then eliminated. The schematic of such a setup is given in Fig. 5. Again, the resistance measured follows Equation (3) where it is equal to the voltage drop measured over the current supplied to the electrodes.

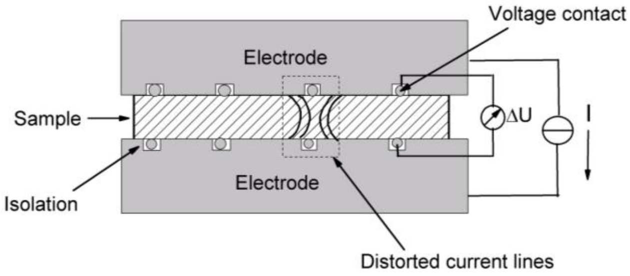

Figure 5: Gold wire electrode setup

Similarly to using a contact pin as the probe, the use of isolation around the gold wires as well as the wire itself creates an area where the iso-potential field is disturbed. This deformation again results in the underestimation of the resistance of the sample. However, as the isolation width in this setup is 50 µm versus the 700 µm for the pin setup, and then the error of such a deformation is decreased. The high in-plane electrical conductivity of the samples along with the small isolation width result in an error of less than 10% associated with this technique. The sample used in this measurement has a diameter of 20 mm.

3.4 Results

The through-plane electrical resistance was measured using the above three techniques for both carbon paper types. As can be seen from Figures 6 and 7, the measured value is dependent on the technique utilized. As expected, the measured values with the gold-coated steel electrodes are higher than that measured with the other two techniques. This is mainly attributed to the high contact resistance between the electrodes and the sample. Further, a reduction in this deviation is seen as the compression is increased as the contact is improved. Further, from Figure 6, it is seen that the resistance measured with the gold pin is lower than that with the gold wire. Again, this is expected as the isolation gap in the pin setup is higher than that of the wire setup; hence, causing a higher deformation in the current lines and further underestimating the resistance. It should also be mentioned that we were unable to measure the resistance of SGL 10 BA with the gold pin setup, despite the carbon paper being thick. This is mainly attributed to a combination between the carbon paper's relatively low in-plane conductivity and moderate through-plane conductivity. The degree to which the iso-potential lines deform within the sample is not only governed by the isolation gap, but also the in- and through- plane resistivity/conductivity of the material.

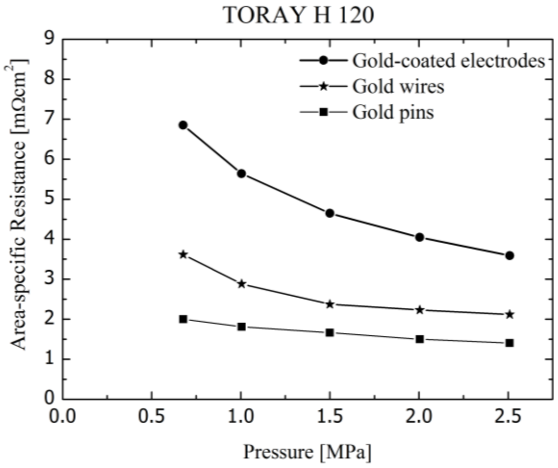

Figure 6: Through-plane area specific resistance of TORAY H 120 versus pressure using various measurement techniques

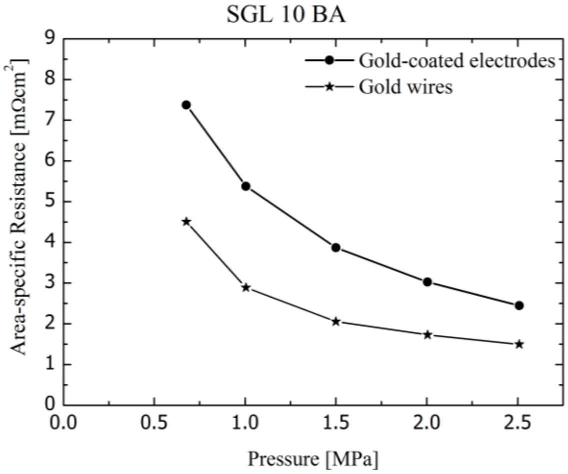

Figure 7: Through-plane area specific resistance of SGL 10 BA versus pressure using various measurement techniques

4. Conclusion

1. For the measurement of the through-plane electrical resistivity of the gas diffusion media, three techniques were discussed. Each technique has advantages and disadvantages. When measuring the resistivity with coated electrodes, it is difficult to completely eliminate the contact resistance to the sample. However, the measurement can be used in numerical models to mimic the resistance originating from the contact resistance between a bipolar plate and the GDL as well as the bulk resistance of the GDL.

2. In order to choose the best measurement technique, it is important to understand the microstructure of the material under investigation.

3. Although the measurement principle of the through-plane electrical conductivity of the GDL is straight forward, problems associated with this technique are mainly due to contact. Prior to the measurement, the electrodes must be properly cleaned and aligned to ensure accuracy of results.

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