Resistance Measurement of Conductive Thermoplastic Bipolar Plates for Polymer Electrolyte Membrane Fuel Cells

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Abstract
Electrical conductivity is one of the most important properties of bipolar plates (BPs). It is, therefore, important to identify possible factors that have a significant effect on bipolar plate electrical resistance measurement techniques. A method for measuring the resistance of conductive thermoplastic BPs for polymer electrolyte membrane fuel cells is described. The major goals of this research are to identify the factors affecting electrical resistance measurements. For BPs made of the same material, dimensional factors such as surface area, thickness and the ratio of surface area over thickness (S/T) could have significant effects on BP resistance measurements. Electrical contact resistance between a gas diffusion layer and a BP is another factor affecting the BP resistance measurement in addition to the surface area and S/T ratio. All these factors can affect the measured resistance and change the result even with the same material. External factors such as clamping pressure applied on the measured BP also reduce the interfacial contact resistance significantly.

Keywords: *PEM fuel cell, Bipolar plate, Resistance measurement, Contact resistance, Electrical conductivity*

1 Introduction

Polymer electrolyte membrane (PEM) fuel cells are the most suitable fuel cell technology for use in automobile applications. However, the high cost of PEM fuel cells has become one of the major barriers limiting fuel cell commercialization. The U.S. DOE provided research that validated the cost estimation and concluded that a cost of \$60 to \$80/kW is the valid approximation of an automotive fuel cell cost when extrapolated to high volumes [1]. The analysed cost of an 80-kW_{net} automotive PEM fuel cell system based on 2013 technology was projected \$55/kW when fabricated at 500,000 units/year and \$67/kW at 100,000 units/year [2]. Bipolar plate, which is one of the main components of a PEM fuel cell, bipolar plates represent approximately 7% of a PEM fuel cell subsystem [1] and 55% of a fuel cell weight [3]. As a result, it is very important that bipolar plates can be made inexpensively and can be mass produced. Bipolar plates require high electrical conductivity; possess adequate mechanical properties and thermal stability and exhibit low contact resistance

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[4,5]. These properties allow the bipolar plate to function distributing oxidant gas and fuel gas, provide the fuel cell's mechanical strength, complete the electrical circuit and regulate the cell temperature. Several types of materials are currently used in bipolar plates, including non-porous graphite plates, metallic plates with or without coating and a number of composite plates [6,7]. Disadvantages of graphite plates are their high costs, high brittleness and the difficulty of machining flow channels. To replace the high cost graphite bipolar plates, extensive research has been conducted for metal-based bipolar plates. Unluckily, the major weakness of metal bipolar plates is their defencelessness to corrosion and dissolution in the PEM fuel cell operating environment of 80°C and a pH of 2-3 [8]. Recently, polymer matrix composites have been investigated for use in the manufacture of bipolar plates. A composite bipolar plate is a promising alternative to graphite and has the advantage of low weight, ease in machining, good corrosion resistance and low cost. The weakest point of the composite bipolar plates is their low electrical conductivity that is compared to metallic or the conventional graphite bipolar plates [9,10]. Therefore, extensive research efforts have been conducted on increasing the conductivity of bipolar plates by applying different conductive fillers [11]. The better the electrical transport of a bipolar plate, the fewer plates are required to produce a given power output. The smaller amount of bipolar plates causes to a smaller fuel cell and lower cost, which are dominant features for market acceptance. A PEM fuel cell is typically constructed in a periodic series of membranes coated by a catalyst layer, gas diffusion layers (GDLs), bipolar plates and current collector plates [12,13]. The components are clamped within two endplates (Figure1).

Individual cells are arranged in a stack and the fuel cell stack contains a multitude of single cells stacked up. A cathode electrode of a single cell is electrically connected to an anode electrode of an adjacent cell. In this connection the same current passes through each single cells (Figure 2). Several researchers and companies have been manufacturing highly novel polymeric composite bipolar plates. They want to test bipolar plate materials in order to identify materials and processes that give a proper ability, especially; their electrical conductivity, for a PEM fuel cell application. Only a few research efforts focus

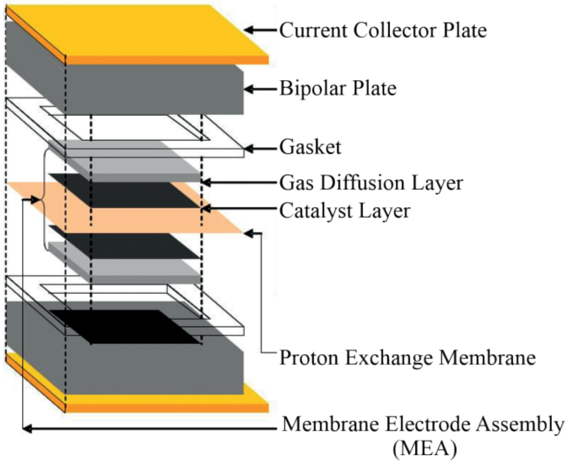

Figure 1: Major components of a PEM fuel cell [14].

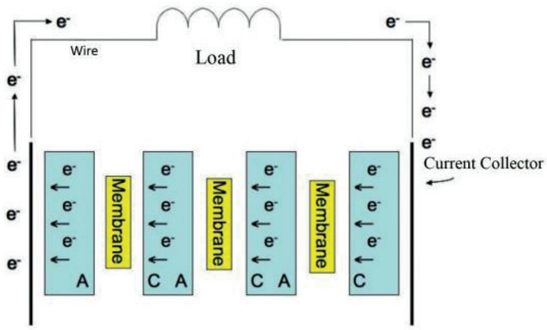

Figure 2: Schematic of electron transport in the PEM fuel cell stacks [15].

on conductivity measurement procedures and factors that can significantly affect electrical conductivity measurement results.

According to Figure 2, contact resistance in a fuel cell stack coming from the interface between GDLs and the bipolar plates is one of major sources to decrease the performance of a PEM fuel cell system. A poor interface contact will decrease the actual area in contact, leading to a voltage drop across the material interface. Mishra and Yang found that the electrical contact resistance between a GDL and flow channels of a bipolar plate is one of the important factors contributing to the operational voltage drop in PEM fuel cells. The measured contact resistances are reported over a range of clamping pressures for various paper-based and cloth-based GDLs [16]. As is well known, the resistance of a material with thickness

T and surface area A can be calculated by equation (1) [17].

$$R_{material} = \rho_Z \frac{T}{A} \quad (1)$$

Where, $R_{material}$ is the material's electrical through-plane sheet resistance (ohm.cm^2) and ρ_z refers to the through-plane electrical resistivity (ohm-cm). From equation (1), we can determine that thickness T and surface area A of the material affect the through-plane resistance of materials. Among composite bipolar plate conductivity testing results, there is no detailed description on the conductivity measurement procedures, especially on the information of test sample dimensions such as shape, thickness and surface area. Nicolas Cunningham [18] described an apparatus for measuring through-plane conductivity and calibration methods. Cunningham found that some factors can affect measurement accuracy and reproducibility, such as the method used to polish the copper electrodes, the contact between the electrodes and the sample and whether disks were used or not. They pointed out that in standard experiments, the measured resistance is caused not only by the resistance of sample ($R_{material}$) but also by the contact resistances of all interfaces in the measured system. Equations derived to calculate measured resistance of a testing system are as follows :

$$R_{meas} = \frac{V_{meas}}{I_{meas}} = R_{material} + R_{system} \quad (2)$$

$$R_{meas} = R_{inst} + R_{\mathrm{int}} \quad (3)$$

Combine equation (2) and (3),

$$R_{meas} = R_{material} + R_{inst} + R_{\mathrm{int}} \quad (4)$$

where V_{meas} and I_{meas} refer to the measured voltage and current; R_{inst} is the systematic error caused by the instruments and R_{int} includes all the interfacial resistances and the intrinsic resistances of carbon cloth or gold plates. However, most research efforts use equation (5) to calculate the bulk resistance of the measured material (R_{plate}) [19]:

$$R_{plate} = \frac{V_{meas} A_{plate}}{I_{meas}} \quad (5)$$

As Nicolas and Michel pointed out, it is impossible to distinguish the resistance caused by the system from the bulk resistance of the measured material. The stack of bipolar plates in a general fuel cell system is compressed under pressure to seal the interfaces. The stress provided to the cell system affects the electrical characteristics of the bipolar plate material; hence, to measure the electrical conductivity of a bipolar plate, a plate must be placed under pressure. Quantum experts created a test station consisted of a bench press that simulate the operational conditions of a fuel cell stack [20]. Nevertheless, the correspondence between measured results and actual in-stack performance has not been standardized. The ability to test bipolar plates under different pressure levels is required. Bac2 Ltd. extended the through-plane conductivity tester that is reliable evaluation for composite bipolar plates [21]. In this system, two gold plaque electrodes containing isolated gold pin are positioned above and below a bipolar plate and the system applies a forced contact in a Z-direction. This procedure instantaneously determines the pressure dependent surface and bulk electrical conductivity contributions from the plates.

2 Experimental Procedures

2.1 *Apparatus*

The sample resistance was measured with the method recommended by the U.S. Fuel Cell Council. A photograph and two schematics of the experimental setup are shown in Figure 3 and Figure 4.

The system of resistance measurement included a CARVER hydraulic press for providing a series of prescribed clamping pressures, a power source and a dual input high-precision digital multi-meter for capturing the electrical voltage and current. Two pieces of GDLs were placed on either side of the bipolar plate and the assembly were placed between two gold-nickel-copper plates. Two polymeric plates were placed between the platens of the press and the gold plates to insulate the electric circuit from the metal press. A clamping pressured up to 4.448×10^4 N was applied and both voltage and current were

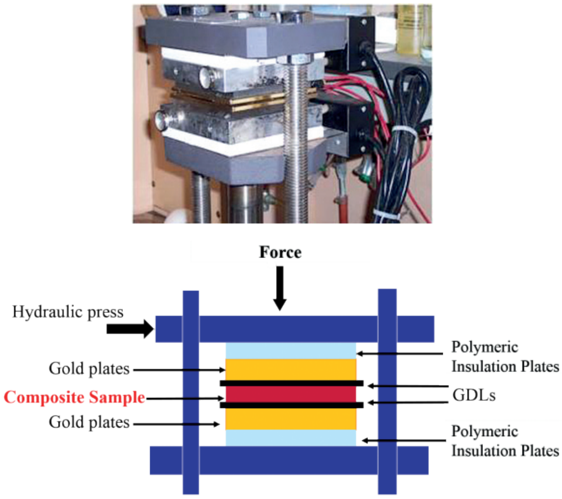

Figure 3: Photograph and schematic diagram of bipolar plate resistance measurement setup.

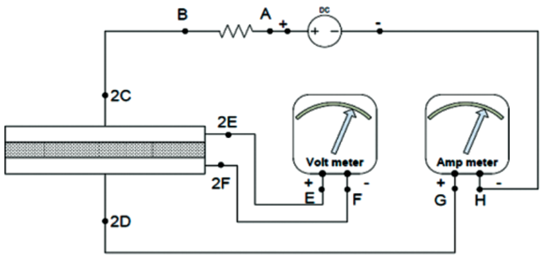

Figure 4: Schematic of electrical circuit for the electrical conductivity measurement.

independently monitored on the both electrodes for the calculation of the total resistance. The clamping pressure correlates to the compressive force applied for assembling a small single cell (using bipolar plates with a 16 cm^2).

2.2 *Conductive polymer composite*

The polymer composite used in this research includes a polymer matrix and three types of carbon-based fillers. The thermoplastic resin chosen is Equistar polypropylene copolymer (Petrothene PP36KKJ01) with 7 of melt flow index and the three kinds of conductive fillers are vulcan carbon black, actylene carbon black and carbon fibers, respectively. They provided by Cabot Corporation, Chevron Phillips Chemical's and Fortafil, respectively. The specific conductive composite content is 71 wt% PP and 29 wt% fillers, which included 21 wt% vulcan carbon black, 4 wt% actylene carbon black and 4 wt% carbon fibers. This created composite formula was selected from preliminary investigation and earlier work demonstrated the effects of filler concentrations and filler loading ratios on the electrical resistance of composite bipolar plates.

2.3 *Gas diffusion layers*

A chosen gas diffusion layer was provided by Ballard Material Products Inc., AvCarbTM 1071 with a thickness of 280 - 432 microns. AvCarbTM 1071 is recommended be used for PEM fuel cells.

2.4 *Bipolar plate sample fabrication*

A bipolar plate was fabricated with conductive composite pellets by hot-pressing under 232 - 244°C of temperature and compression forces up to 2.224×10^4 N.

The dimensions of different moulds used for making sample plates are illustrated in Table 1. The sample plates were used to determine the effect of surface area (S), surface area/thickness (S/T) and thickness independently on the resistance of the bipolar plate.

Table 1: The dimensions of sample plates

Samples	Width (mm)	Length (mm)	Thickness (mm)
1	100.00	100.00	3.10
2	59.50	24.30	5.95
3	70.00	28.00	1.27
4	100.00	49.00	3.10
5	61.00	51.00	3.10
6	51.00	38.00	3.10

2.5 *Bipolar plate resistance measurement*

The total electrical resistance of the entire system is a summation of the bulk resistance of the two gold plates, $2R_{Au\text{-}Cu}$, the bulk resistance of two gas diffusion layers, $2R_{GDL}$, the bulk resistance of bipolar plate, R_{plate}, the two interfacial contact resistances between the GDL and the bipolar plates, $2R_{p/GDL}$ and the two interfacial contact resistances between the gold plate and gas diffusion layer, $2R_{Au/GDL}$.

The nomenclature of all resistance (Figure 5) in the system is as follows:

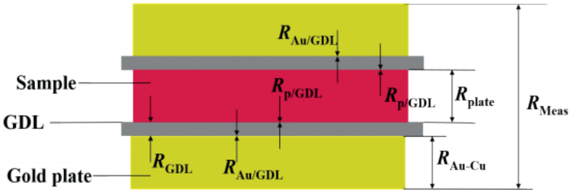

Figure 5: Schematic diagram of resistance test analysis of bipolar plate.

R_{meas} = measured resistance;
R_{plate} = resistance of bipolar plate sample;
R_{GDL} = resistance of gas diffusion layer;
R_{Au-Cu} = resistance of gold-nickel- copper plate;
$R_{Au/GDL}$ = contact resistance caused by an interface between GDL and the gold plate;
$R_{p/GDL}$ = contact resistance caused by an interface between GDL and the bipolar plate sample;

The expression for the total measured resistance for the assembly is given as

$$R_{meas} = 2R_{Au\text{-}Cu} + 2R_{GDL} + 2R_{p/GDL} + 2R_{Au/GDL} + R_{plate} \quad (6)$$

In fact, the values of R_{GDL} and R_{Au-Cu} are very small (<<1), since the GDL and gold plate are very conductive. Therefore, we can neglect the effect of R_{GDL} and R_{Au-Cu} on the total measured resistance, R_{meas} and equation (6) can be simplified to equation (7):

$$R_{meas} = 2R_{Au/GDL} + 2R_{p/GDL} + R_{plate} \quad (7)$$

In equation (7), the measured resistance, R_{meas}, was determined by the contact resistance between the GDL and the gold plate, $R_{Au/GDL}$, the contact resistance between the bipolar plate and GDL, $R_{p/GDL}$, as well as the bulk resistance of the bipolar plate sample, R_{plate}. If the values of the two contact resistances are as small as possible, the measured resistance relatively is equal to the bulk resistance of the bipolar plate. In other words, the bulk resistance of the bipolar plate can be accurately measured by minimizing the contact resistances in the testing system caused by the interface between the bipolar plate and GDLs and the interface between the GDL and gold plates.

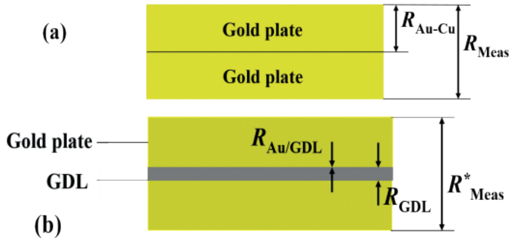

Figure 6: (a) Schematic diagram of resistance measurement analysis of gold plate and (b) gas diffusion layer.

3 Results and Discussion

Electrical conductivity is one of the most important properties of bipolar plates. Moreover, it is important to realize that the size or dimension of bipolar plates may have a significant effect on electrical resistance measurement. Experimental studies were conducted on bipolar plates (same material) with different surface areas and thicknesses in contact with GDLs, with following objectives: to identify the resistance of the gold plates and GDLs as well as the contact resistance between the gold plate and the GDL; to investigate the influences of sample surface area, thickness and ratio of surface area over the thickness of bipolar plates on contact resistance measurements; to study the effect of clamping pressure on bipolar plate resistance measurements.

3.1 R_{GDL} and R_{Au-Cu} measurement

From equation (6), in order to measure the bulk resistance of bipolar plates (R_{plate}) accurately, the bulk resistances of the gold plates and GDLs must be evaluated and subtracted from the total measured resistance of the assembly. The bulk resistance of gold plate, R_{Au-Cu}, can be determined by independent measurement involving only the two gold plates put together as shown in Figure 6(a), the bulk resistance of the GDLs, R_{GDL}, can also be determined by independent measurement involving only the GDL sandwiched between the two gold plates shown in Figure 6(b). Based on this new setup in Figure 6(b), the total measured resistance, R^*_{meas}, is expressed in equation (8).

$$R^*_{meas} = 2R_{Au\text{-}Cu} + 2R_{Au/GDL} + R_{GDL} \quad (8)$$

If R^*_{meas} was substracted by the total measured resistance then equation (6) is further expressed as

$$R_{meas} - R^*_{meas} = R_{GDL} + 2R_{p/GDL} + R_{plate} \quad (9)$$

According to the testing results as showed in Table 2, the average value of $R_{Au\text{-}Cu}$ is only 3.2×10^{-6} ohm which is insignificant with respect to the total resistance of the system and is therefore negligible.

Table 2: Testing results of gold plate resistance

Resistances (Ω)	Sample 1	Sample 2	Sample 3	Average
R_{meas}	5.5×10^{-6}	6.8×10^{-6}	7.2×10^{-6}	6.5×10^{-6}
$R_{Au\text{-}Cu}$	2.7×10^{-6}	3.4×10^{-6}	3.6×10^{-6}	3.2×10^{-6}

For a piece of GDL with a dimension of 100.43 × 100.35 × 0.42 mm, sandwiched between two gold plates with a series of loading forces, the measured resistances for this arrangement are shown in Table 3. The resistance data are in the range of 0.000021 to 0.000084 Ω, which are very low values compared to the total resistance experienced in actual fuel cell operation environments. Based on the values of R_{GDL} and $R_{Au\text{-}Cu}$, the contributions of R_{GDL} and $R_{Au\text{-}Cu}$ to the total measured resistance of bipolar plate assembly are negligible. Moreover, since GDLs are highly conductive material compared to the bipolar plates, the contribution of the bulk resistance of gas diffusion layers can also be regarded as negligible within the resistance measurement assembly. As a result, the equation (9) is further simplified to

$$R_{meas} \approx 2R_{p/GDL} + R_{plate} \quad (10)$$

In equation. (10), the total measurement resistance of the bipolar plates and the GDL assembly is the summation of the bulk resistance of bipolar plate, R_{plate}, the two interfacial contact resistances between the GDL and bipolar plate, $2R_{p/GDL}$. It is obvious that except for the intrinsic bulk electrical resistance of a bipolar plate, R_{plate}, the interfacial contact resistances between the GDL and bipolar plate, $2R_{p/GDL}$, also have a significant effect on the total measured resistance. Hence, it is very important to identify the factors that affect the $R_{p/GDL}$ and to minimize the effect of interfacial contact resistance on the total measured resistance.

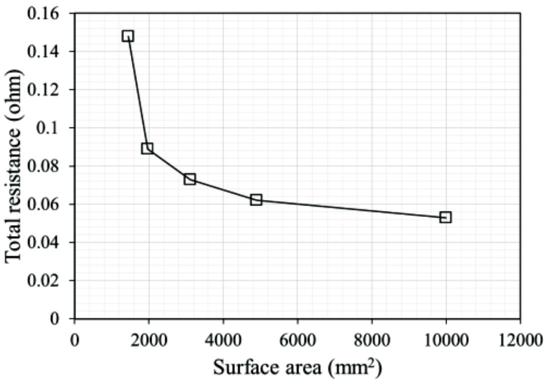

Figure 7: Resistance of GDL/bipolar plate assembly at various surface area.

Table 3: Resistance measurement of GDL

GDL dimensions	Force (N)	Pressure (kPa)	RGDL (Ω)
Length: 100.43 mm. Width: 100.35 mm. Thickness: 0.42 mm.	4.448×10^{3}	4.412×10^{2}	8.4×10^{-5}
	8.896×10^{3}	8.825×10^{2}	5.6×10^{-5}
	1.335×10^{4}	1.324×10^{3}	4.2×10^{-5}
	1.780×10^{4}	1.765×10^{3}	3.5×10^{-5}
	2.224×10^{4}	2.206×10^{3}	2.1×10^{-5}

3.2 *Dimentional effect on resistance measurement*

3.2.1 Effect of sureface area

Figure 7 shows the total resistance as a function of surface area for GDL/Bipolar plate assembly, where bipolar plates have various thicknesses and the applied loading force is 2.224×10^4 N. The measured resistance (ohm) is decreased with increasing surface area. The contact area between GDL and bipolar plate increases correspondingly as the surface area increases.

In this case, the contribution of interfacial contact resistance between the GDLs and bipolar plates become more significant than that of the bulk resistance of bipolar plate with respect to the total measured resistance. With increasing surface area, the bulk resistance of the bipolar plate is decreased, which lead to the decrease of the total measured resistance of a system. It seems that as the contact area or surface area of bipolar plate reaches infinity, the bulk resistance can become negligible (based on equation (1)) and the total measured resistance can be that of the two interfacial contact resistance between the GDLs and the bipolar

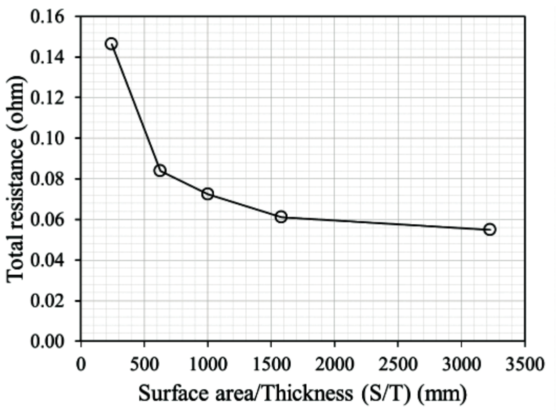

Figure 8: Resistance of GDL/bipolar plate assembly at various sizes and S/T.

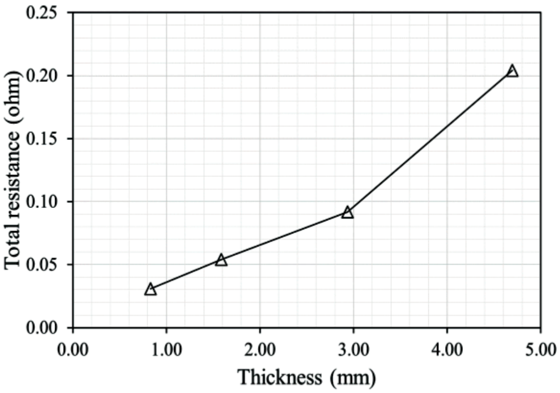

Figure 9: Resistance of GDL/bipolar plate assembly at various sizes and S/T.

plates. Please note that the composite bipolar plate specimens that were used for these experimental tests did not contain flow channels, since this technique was used to measure the electrical resistance of novel composite bipolar plates as an ex-situ test. The ex-situ test is typically employed for material property observations. The appropriate specimen geometry are important for the electrical resistance investigation to ensure that the resistance mainly comes from the material property. Bipolar plates with flow channels will be used to measure fuel cell resistance and performance via in-situ test using an electrochemistry technique.

3.2.2 Effect of S/T ratio

Figure 8 represents the resistance of the GDL/bipolar plate assembly as a function of the ratio of surface area over thickness (S/T).

With increasing S/T, the measured resistance (ohm) decreases. This tendency is similar to that of Figure 7 in which the measured resistance decreases with increasing surface area. Similarly, with increasing S/T, the bulk resistance of the bipolar plate will decrease significantly and the contact resistance between the GDL and bipolar plate has more contribution on the total measured resistance. It is clear that due to the geometric difference of the various bipolar plates, the measured resistance can be significantly different. If there were procedures recommending plate geometry, it would be much easier to successfully compare conductivity results between different composite materials.

3.2.3 Effect of thickness

The effect of thickness on resistance measurement was also investigated in this work. Bipolar plates of the same area but with different thicknesses were measured. Figure 9 shows the bipolar plate resistances as a function of thickness for samples with the same surface area. The measured resistance increases with increasing thickness of the bipolar plate, contributing to increased bulk resistance. The summary of the bulk resistances and the two contact resistances between the bipolar plate and gas diffusion layer, R_{plate} and $2R_{p/GDL}$, forms the dominant part of the total resistance shown in Figure 9. The lower value of R_{meas} corresponds to the thinner bipolar plate of 0.8 mm thickness and the higher R_{meas} value corresponds to the thicker, 4.7 mm of bipolar plate thickness.

In both cases, the bulk resistance of the bipolar plate makes a more significant contribution to the total measured resistance than the contact resistance. However, if the thickness of the bipolar plate is as thin as possible, similarly, the bulk resistance is also negligible and the measured resistance is equal to the two contact resistances between the GDL and bipolar plate.

3.2.4 Effect of clamping pressure

The resistances of the bipolar plates were also measured at conditions with different loading forces. Forces applied to the interface leads to the increase in the contact area between a bipolar plate and GDL, which in turn, decreases the interfacial contact

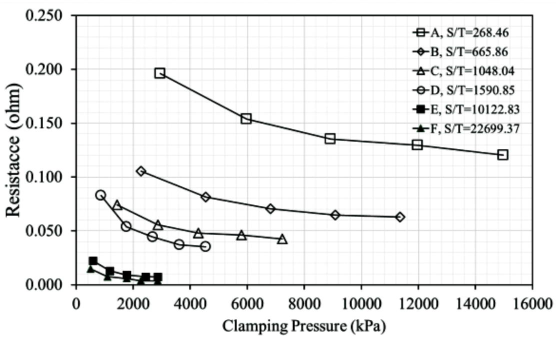

Figure 10: Effect of clamping pressure on measured resistance.

resistances. Loading forces that were applied include 4.448×10^3, 8.896×10^3, 1.335×10^4, 1.780×10^4 and 2.224×10^4 N respectively. Converted applied pressures vary depending on force and sample dimentions. The measured resistance results are shown in Figure 10. As anticipated, the measured resistance decreases with increasing clamping pressure for all bipolar plate samples with different ratios of surface area over thickness (S/T). The highest resistance was observed for the bipolar plate with smaller S/T ratios (for example, S/T = 268.46 mm). For a wide range of clamping pressures a change in measured resistance is not very significant. While with increasing S/T values (from 268.46 mm to 22699.37 mm), the measured resistance decreases dramatically, in other words, the higher value of S/T, the lower the resistance measured. Also for higher S/T ratios, the measured resistance can also be decreased over a narrow range of clamping pressures.

In the case of bipolar plates with higher values of S/T, the contribution of contact resistance between the GDL and the bipolar plate to the measured resistance is more significant than the bulk resistance of bipolar plate. The contact resistance between the GDL and bipolar plate with unknown conductivity can be estimated as S/T reaching very large (infinite) values, an estimation that in turn can enable the actual bulk resistance of the bipolar plate to be measured accurately. Two possible reasons can be used to explain the contact resistance reduction. First, forces applied to the interface lead to an increase in the contact area between a bipolar plate and GDLs, which in turn, decreases the interfacial contact resistances. Second, carbon fibers in GDLs penetrate into the surface of composite bipolar plates and so conductive paths are propagated.

4 Conclusions

This work investigated the factors affecting the resistance measurement of conductive thermoplastic bipolar plates for polymer electrolyte membrane fuel cells. The aim of this research is to understand the relative significance of contact resistance to bulk conductivity, which is important for fuel cell bipolar plate design and bipolar plate material selection. For the same bipolar plate material, dimensional factors such as surface area, thickness as well as the ratio of surface area over thickness of bipolar plates has a significant influence on bipolar plate resistance measurements. One if the important factor affecting bipolar plate resistance measurements is the electrical contact resistance between the gas diffusion layer and the bipolar plate and this factor is focused on in this work. Surface area and surface-area-over-thickness ratio of bipolar plates show significant effects on the interfacial contact resistances and as a result, the measured resistance of the same material is vary significant. At a high-surface-area-to-thickness ratio, contact resistance is most significant. Other factors such as thickness, material properties, surface geometry and clamping pressure also affect bipolar plate resistance measurements significantly. Some variables, such as bipolar plate manufacturing and surface treatment processes, may affect significantly on the contact resistance of the plates. The effects of the processes on electrical properties of bipolar plates are, therefore, an interesting issue for a further study.

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References

[1] IPHE, “Fuel cell cost analysis summary,” in *International Partnership for Hydrogen and Fuel Cells in the Economy*, China, Dec. 2008.

[2] J. Spendelow and J. Marcinkoski, “Fuel Cell System Cost - 2013,” Department of Energy, USA, Record #13012, Oct. 16, 2013.

[3] K. Jayakumar, S. Pandiyan, N. Rajalakshmi, and K.S. Dhathathreyan, "Cost-benefit analysis of commercial bipolar plates for PEMFC's," *Journal of Power Sources*, vol. 161, pp. 454-459, 2006.

[4] V. Mehta and J.S. Cooper, "Review and analysis of PEM fuel cell design and manufacturing," *Journal of Power Sources*, vol. 114, pp. 32-53, 2003.

[5] J.S. Cooper, "Design analysis of PEMFC bipolar plates considering stack manufacturing and environment impact," *Journal of Power Sources*, vol. 129, pp. 152-169, 2004.

[6] A. Hermanna, T. Chaudhuria, and P. Spagnol, "Bipolar plates for PEM fuel cells: a review," *International Journal of Hydrogen Energy*, vol. 30, pp. 1297-1302, 2005.

[7] S.S. Dihrab, K. Sopian, M.A. Alghoul, and M.Y. Sulaiman, "Review of the membrane and bipolar plates materials for conventional and unitized regenerative fuel cells," *Renewable and Sustainable Energy Reviews*, vol. 13, pp. 1663-1668, 2009.

[8] H. Tawfika, Y. Hunga, and D. Mahajan, "Metal bipolar plates for PEM fuel cell - a review," *Journal of Power Sources*, vol. 163, pp. 755-767, 2007.

[9] T.M. Besmann, J.W. Klett, J.J. Henry, C.E. Lara, "Carbon/carbon composite bipolar plate for PEM fuel cells," *Journal of The Electrochemical Society*, vol. 147(11), pp. 4083-4086, 2000.

[10] Z. Bin and M. Bingchu, "Study on the electrical and mechanical properties of poly vinylidene fluroide/titanium silicon Carbide composite bipolar plates," *Journal of Power Sources*, vol. 161, pp. 997-1001, 2006.

[11] A. Maaroufi, K. Haboubi, A.E. Amarti, and F. Carmona, "Electrical resistivity of polymeric matrix loaded with nickel and cobalt powders," *Journal of Materials Science*, vol. 39, pp. 265-270, 2004.

[12] F. Barbir, *PEM fuel cell*, UK: Elsevier Inc., 2005, pp. 1-16.

[13] R. O'Hayre, S-W. Cha, W. Colella, and F.B. Prinz, *Fuel cell fundamentals*, USA: john Wiley&Sons, Inc., 2009, pp.1-25.

[14] Fuel cell store (2014, July 12). *PEM Fuel Cell Hardware*. [Online]. Available: http://fuelcellstore.com/pem-fuel-cell-hardware-test-stack

[15] R. Yeetsorn, M.W. Fowler, and C. Tzoganakis, "A review of thermoplastic composites for bipolar plate materials in PEM fuel cells," in *Nanocomposites with unique properties and applications in medicine and industry*, J. Cuppoletti Ed. Croatia: INTECH, 2011, pp. 318-343.

[16] V. Mishra, F. Yang, and R. Pitchumani, "Contact resistance between gas diffusion layers and bipolar plate for applications to PEM fuel cells," *Transactions of the ASME*, vol. 1, pp. 1-9, 2004.

[17] J.W. Kim and N.H. Kim, "Synergy effects of hybrid carbon system on properties of composite bipolar plates for fuel cells," *Journal of Power Sources*, vol. 195, pp. 5474-5480, 2010.

[18] N. Cunningham, M. Lef`evre, G. Lebrun, and J.-P. Dodelet, "Measuring the through-plane electrical resistivity of bipolar plates (apparatus and methods)," *Journal of Power Sources*, vol. 143, pp. 93-102, 2005.

[19] H. Wang, M.A. Sweikart, and J.A. Turner, "Stainless steel as bipolar plate material for polymer electrolyte membrane fuel cells," *Journal of Power Sources*, vol. 115, pp. 243-251, 2003.

[20] L. Landis and J.L. Tucker, *Making better fuel cells: through-plane resistivity measurement of graphite-filled bipolar Plates*, Ohio, USA: Quantum Composites Inc. and Keithley Instruments, Inc., 2007.

[21] J. Doyle and G. Murray, *Evaluating the three-dimensional electrical conductivity of composite bipolar plates*, UK: Bac2 Ltd., 2011.