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A review of electrical conductivity models for conductive polymer composite

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ABSTRACT

Conductive Polymer Composite (CPC) can be considered one of the best material candidates for the bipolar plates in Polymer Electrolyte Membrane (PEM) fuel cells due to its balance between electrical and mechanical properties, low cost and ease of manufacturing. The development of the models has been shown to be important for predicting the electrical properties of the CPCs. The main challenge is to produce a constant electric supply in the fuel cell systems which influence the overall fuel cell performance. Generally, the classical percolation theory describes that the electrical conductivity of the polymer composite is achieved when the volume fraction of the conductive filler is above the specific value, known as percolation threshold phenomena. Current research trends using the General Effective Media (GEM) model show it is the best model to predict the electrical properties of the composite. The main advantage of using the GEM is the model can predict the electrical conductivity for multiple filler systems at high filler loadings. Numerous factors including volume fraction, shape and size, aspect ratio, critical value, and orientation are significant in developing a robust model. Controlling the filler orientations in the CPCs are important as they are able to improve the mechanical performance while enhancing the electrical conductivity of the composite. Orientation can be induced by a few methods such as shear stress, altering die and fillers aspect ratio based on the needs. By controlling the fillers direction, one is able to control both the mechanical and electrical conductivity of the CPCs. However, recent publications seem to suggest that the Fibre Contact Model (FCM) is the latest model that considers the orientation factor in predicting conductivity. A good agreement between experimental results and modelling prediction can be observed using carbon-fibre reinforced polypropylene below and above the percolation threshold. Parallel orientations of the fibres to the extrusion die direction provided better electrical conductivity compared to randomly oriented fillers. This manuscript attempts to discuss other potential models used in predicting the electrical conductivity of the CPCs.

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Introduction

Conductive Polymer Composites (CPCs) are obtained by mixing an insulating polymer matrix with conductive fillers such as Carbon Black (CB), Carbon Fibres (CF), carbon nanotube (CNT) or any relevant filler particles which produce a good conducting pathway through the polymer matrix [1]. CPCs exhibit several interesting features such as high electrical conductivity, light weight, corrosion resistant and good mechanical properties performance [1–3]. Nevertheless, its morphology and structure of conductive network pathways within the composite matrix are the key parameters for better electrical conductivity of the CPCs [2]. Current technology has offered CPCs in various of applications including sensors, components in circuit devices, battery, fuel cell electrodes and fuel cell bipolar plates [1,3–9].

In order for the material to become electrically conductive, the concentration of the conducting phase must be above the percolation threshold as described in detail by the percolation theory. The correlation that exists between the electrical conductivity of the filler particles in various polymer matrix and filler concentrations usually depends on the volume fraction of the components and the filler morphology [10,11]. The percolation theory is categorized into two main regions; below the percolation threshold and above the percolation threshold. In the region below the percolation threshold, the electrical conductivity is equivalent to the electrical conductivity of the insulating polymer matrix at low filler loadings as the filler particles are dispersed without developing the conductive network throughout the composite. As the filler concentrations increase, continuous conductive networks are developed until a certain critical volume fraction known as the percolation threshold. Beyond the percolation threshold, the conductive network increases as the filler concentrations increase until the electrical conductivity plateau remains flats [11].

Recent studies reported that there are numerous factors that can affect the electrical conductivity of the polymer composite such as filler distribution, shape and size, aspect ratio, filler conductivity and matrix interaction, nature of polymer matrix, wettability, shape, orientation, surface energy and processing technique [1,10–23]. Based on these factors, various models have been proposed in order to predict the electrical conductivity of the composite materials. However, most models usually apply volume fraction as base the calculations in predicting the electrical conductivity of the composite system [11]. In summary, there is still a need to understand the correlation between a proposed model and the experimental value of electrical conductivity. In this manuscript, each model currently used by researchers to predict the electrical conductivity of the CPCs is discussed in detail.

Current development of electrical conductivity model

Recent publications indicate that the conductive polymer composite material had moved to a high filler content especially for bipolar plate applications in fuel cells. The current model used to predict the electrical conductivity of CPCs is the General Effective Media (GEM) model developed by McLachlan. Most researchers applied the GEM model in their studies due to the electrical conductivity obtained that is much closer or above the percolation threshold and it is suitable for multiple filler composites [13,24]. Barton and Leia in their work explained that the GEM model is suitable for multiple or single filler use which fit the resistivity data especially in carbon black fillers [13,25]. The GEM equation shows good agreement between the carbon fibre, carbon black and synthetic graphite with a thermoplastic material, Vectra when compared to experimental data as shown in Fig. 1 [13]. Leia also had the same outcome when the GEM equation fit the experimental data adequately using carbon black [25]. Barton suggested that a higher electrical conductivity of the polymer composite can be achieved when the electrical conductivity of the filler is not far apart which supported by using fillers with higher electrical conductivity which promote a better conductive composite material [26,27].

However, there are still lots of limitations due to contradicting experimental and theoretical results. Models which are made based on an assumption usually cannot fulfil the requirements of every case. The original GEM equation can only predict the electrical conductivity for complex and multiple compositions only when the equation is modified accordingly [28]. Barton proved this using synthetic graphite material, where there was a lack of agreement with the experimental data when non-bulk compress graphite was used [13]. Critical exponent, t (Fig. 1) is determined by the morphology and structure of the conducting particles. A higher t-value which floats between 6 and 8 using regression and is obtained when applied to the graphite flake structure material shows that the t-value is affected by the extreme geometry of conducting particle [10,26]. Barton explained that the t-value of multiple fillers are slightly higher than a single filler due to the combination of different morphology particle and dispersion [26]. Mamunya reported that the t-value seems larger than the universal $t = 1.7$ using the metal-filled polymer in Mamunya's model as the morphological system is anisotropic or in a complex structure material [21]. Moreover, the increase of t-value in multiple fillers might cause the filler particle to orient and create more extreme geometry than single filler composite. Balberg explained that different filler grades with dissimilar size lead to various t-values due to the different filler particles yielding, different kinds of conducting networks [12].

In spite of the fact that researcher had reported that the effective complex parameters of carbon filled composites should depend on fibre properties such as aspect ratio, concentration, conductivity and rate of alignment in order to optimize the oriented carbon fibre and maximize the electrical conductivity [14,29]. It was also reported in a literature by Kakati that the GEM model is not suitable for measuring electrical conductivity in high conductive polymer composite for more than two components in the system for both in-plane and through-plane conductivity due to its anisotropic characteristic [28].

Barton mentioned that through-plane conductivity is not often accounted for in the measurement system of the electrical conductivity as filler directions usually align in a single