Chapter 7

INTERPHASE AND ITS EFFECT ON OPTIMIZING FILLER CONCENTRATIONS FOR IMPROVED DIELECTRIC AND THERMAL PROPERTIES

7.1 INTRODUCTION

High dielectric and mechanical strength are utilized to evaluate the short-term performance of dielectric materials used in high-voltage applications. Electrical insulation in service, on the other hand, ages as a result of the synergistic effect of electro-thermal stress. Low DC conductivity and a low loss tangent minimize power loss within the dielectric, while high thermal conductivity enables efficient heat evacuation. Thus, improved electro-thermal characteristics mitigate thermal degradation and extend the useful life of dielectric materials. Polymers are frequently filled with nanosized inorganic fillers that are electrically insulating but have a higher thermal conductivity than the base polymer. It is critical to determine the filler concentration that improves thermal conductivity without impairing electrical properties. Additionally, as demonstrated in the preceding chapters, the interphase surrounding nanofillers plays a critical role in the change of properties in polymer nanocomposites. Thus, this chapter will investigate the effect of interphase on optimizing the nanofiller content for improved electro-thermal properties.

7.2 METHODOLOGY

A numerical model involving interphase is constructed using insight gained from previous studies. Effective dc conductivity and thermal conductivity of nanocomposites are determined at various filler concentrations for previously determined interphase parameters. The subsections that follow provide additional details on this study.

7.2.1 Estimation of effective electrical conductivity

The effective dc conductivity of nanocomposites is determined according to the procedure described in section 6.2.1.4. The required number of randomly dispersed filler particles are incorporated within a cubical block for each filler concentration. Figure 7.1 shows a typical epoxy block (1μmx1μmx1μm) with 153 alumina nanoparticles, representing a 1 vol.% filler concentrations.

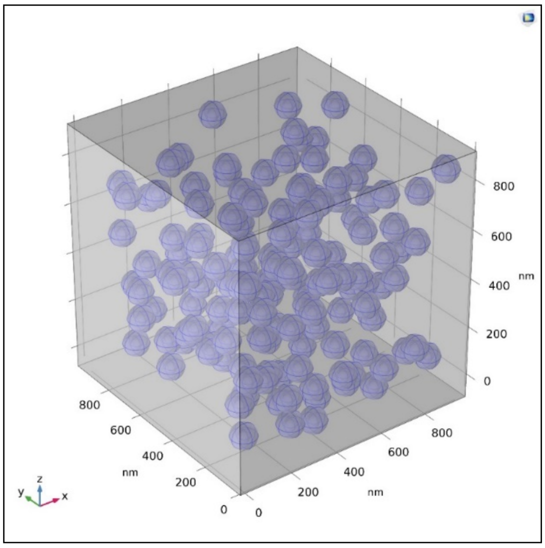

Figure 7.1 Epoxy matrix containing filler nanoparticles

The effective dc conductivity at each filler content is calculated for five sets of randomized filler dispersion. A necessary structure in the JAVA code was created to eliminate particle overlap. The average of five sets is derived as a representative value for each filler content. The computed effective dc conductivity at various filler concentrations is shown in Figure 7.2. At a filler concentration of 1.0 vol.%, the greatest improvement in dc conductivity is found.

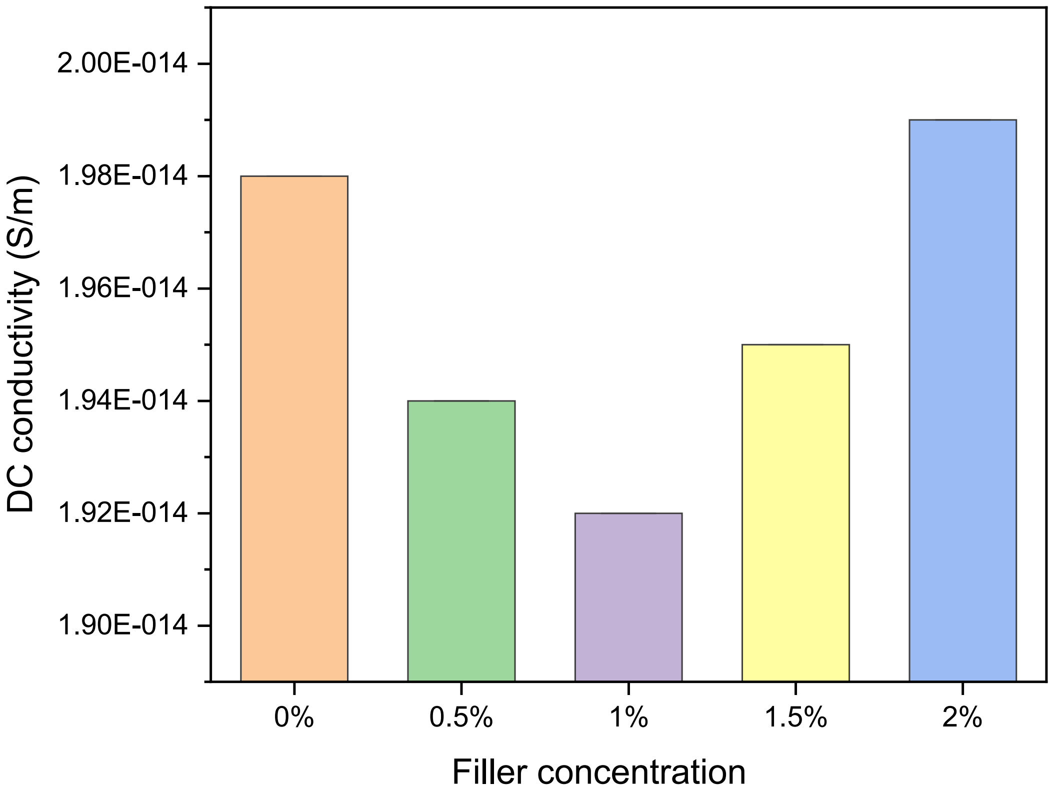

Figure 7.2 Computed effective DC conductivity

7.2.2 Estimation of effective thermal conductivity

The approach outlined in section 6.3.1.2.4 is used to calculate the effective thermal conductivity of nanocomposites. The estimated values of effective thermal conductivity at various filler concentrations are shown in Figure 7.3. With increasing filler concentrations, thermal conductivity exhibits a consistent rise in value.

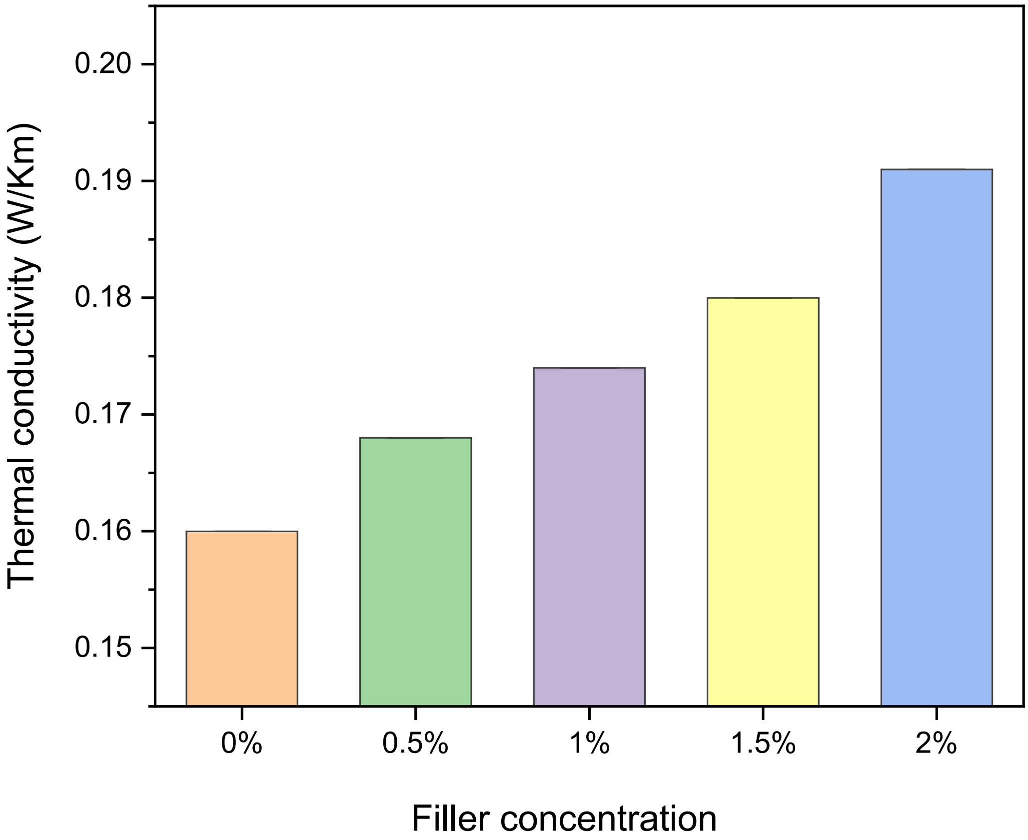

Figure 7.3 Computed effective thermal conductivity

7.2.3 Experimental validation

A series of experiments are conducted at various filler concentrations to validate the numerical computations mentioned previously. DC conductivity is determined by employing the three-electrode configuration described in section 3.2.2. Thermal conductivity is determined using a TPS-500 instrument and the procedure described in section 3.1.3. The DC conductivity and thermal conductivity measurements are summarized in Table 7.1. It is observed that the difference between the measured and numerically computed values is within an acceptable range. Additionally, experimental results demonstrate a trend consistent with that observed in simulation studies.

Table 7.1 Effective dc conductivity and thermal conductivity of nanocomposites obtained from experimental and simulation studies

Properties / Filler content	DC conductivity (S/m)		Thermal conductivity (W/Km)	
	Measured	**Computed**	**Measured**	**Computed**
0 vol.%	1.98E-14	1.98E-14	0.160	0.160
0.5 vol.%	1.946E-14	1.94E-14	0.169	0.168
1 vol.%	1.92E-14	1.92E-14	0.174	0.174
1.5 vol.%	1.958E-14	1.95E-14	0.181	0.180
2.0 vol.%	2.00E-14	1.99E-14	0.192	0.191

7.2.4 Optimizing filler concentrations and role of interphase

As mentioned previously, dielectric property (i.e., dc conductivity) improve as filler content increases. However, the greatest improvement is observed at a filler content of 1 vol. %. Beyond 1 vol. %, dielectric properties begin to deteriorate. As shown in Table 4.1, if nanocomposites are synthesized using surface-treated nanofillers, a fairly uniform dispersion can be achieved up to a filler concentration of 2 vol.%. It is well established that nanocomposites behave differently than traditional micro-composites due to the enormously increased filler matrix interaction zone/or interphase. To better understand the relationship between interphase size and changes in material properties, interphase volume fraction at various filler concentrations is computed. Interphase volume fraction as a function of filler concentrations is depicted in Figure 7.4. For an interphase thickness of 100 nm, the maximum interphase volume fraction occurs at a filler content of 1 vol.%. This indicates that the interphase volume is a significant factor in determining the dielectric properties. The optimal filler content for the best dielectric properties is that at which the interphase volume is maximized.

The thermal conductivity increases monotonically as filler concentrations are increased, provided that filler dispersion is adequate. At a high filler content, thermal conductivity is expected to increase dramatically due to the formation of a conducting network. Thus, filler content is a critical factor in determining the thermal conductivity of nanocomposites. Improved thermal conductivity is desirable in electrical insulating materials, but not at the expense of deteriorated dielectric properties. As a result, the optimal filler concentrations should be determined by the maximum improvement in dielectric properties, not thermal properties. Nonetheless, a trade-off is possible depending on the application area.

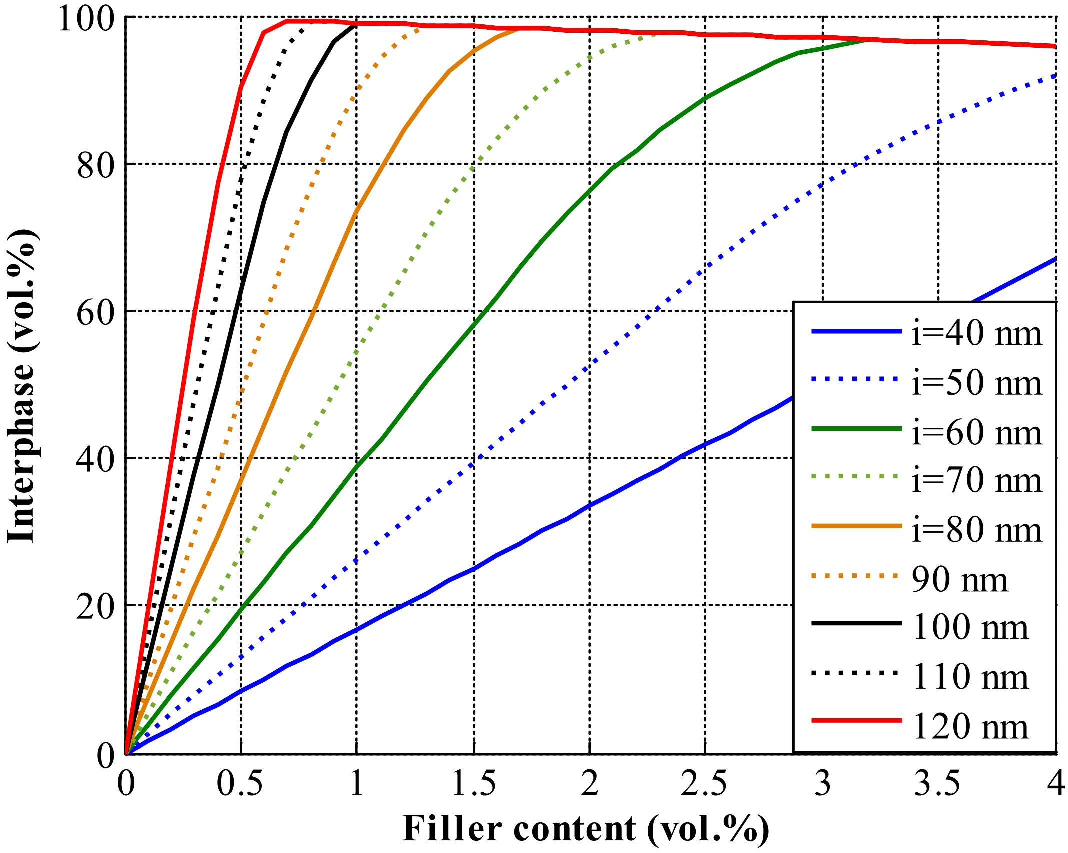

Figure 7.4 Interphase volume fraction vs. filler concentrations characteristics at different interphase thicknesses

7.3 SUMMARY

This chapter emphasizes the importance of considering dielectric materials in a unified framework that incorporates thermal and dielectric properties in order to improve their overall performance. It is concluded from the analysis presented in this chapter that thermal properties are governed by nanofiller concentrations, whereas dielectric properties are governed by interphase volume fraction. As a result, the optimal filler concentrations for enhanced dielectric and thermal properties are those with the highest interphase volume fraction. Beyond this optimal filler concentration, increased thermal conductivity is possible at the expense of degraded dielectric properties.