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DYNAMIC AND NONLINEAR ANALYSIS OF HYBRID EPOXY COMPOSITES: IMPACT OF THICKNESS, AND TRANSIENT BEHAVIOR

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Abstract: This study investigates the thermal and electrical performance of hybrid epoxy composites with varying thicknesses, filler fractions, and nonlinear material behaviors. The effect of composite thickness on conductivity was examined by extensive MATLAB simulations, which showed that while electrical conductivity falls with increasing resistance, thermal conductivity increases with thickness. Higher filler fractions are perfect for dynamic applications since they drastically shorten the time needed to reach steady-state conditions, as shown by transient simulations. By demonstrating how temperature- and voltage-dependent conductivities yield more accurate predictions than linear models, the study further emphasizes the significance of nonlinear modeling. These results highlight how important filler content, composite geometry, and nonlinear effects are when it comes to developing hybrid composites for high-performance uses. Experimental validation, investigation of sophisticated filler configurations, and examination of other nonlinear behaviors are among the suggestions for further research. This research advances the creation of hybrid epoxy composites with improved electrical and thermal characteristics for application in the automotive, aerospace, and electronics sectors.

Keywords and phrases: Hybrid epoxy composites, thermal conductivity, electrical conductivity, transient analysis, nonlinear modeling, MATLAB.

MSC 2010 Classification: 74F05, 78M20, 82D25.

1 Introduction

Hybrid epoxy composites combine the intrinsic qualities of epoxy resin with those of other fillers, making them highly versatile materials in advanced technical applications. These composites are widely employed in sectors where excellent electrical performance and effective thermal management are crucial, including electronics, automotive, aerospace, and telecommunications. They are based on an epoxy matrix, which is renowned for its processability, chemical resistance, and mechanical strength. However, functional fillers must be added to improve the epoxy resin's inherently low electrical and thermal conductivity. Fillers such as graphene, boron nitride, silica nanoparticles, and carbon nanotubes (CNTs) have shown significant promise in enhancing these composites' electrical and thermal properties, enabling them to meet the stringent requirements of high-performance applications [6, 7].

Incorporating fillers into the epoxy matrix enhances its conductivity and allows the composite's properties to be tailored for specific applications. For instance, fillers like boron nitride or silica nanoparticles can significantly improve thermal conductivity, while carbon-based fillers such as graphene and CNTs can enhance electrical conductivity [3, 6]. Despite these advancements, challenges remain in the design and optimization of these composites to fully realize their potential. The current research focuses primarily on how filler types, distribution, and volume fractions affect the properties of hybrid epoxy composites. However, limited information is available about the influence of composite thickness on electrical and thermal performance. In real-world applications, composite thickness plays a crucial role, particularly in multi-layered setups or thickness-sensitive designs. A lack of comprehensive studies on this topic hinders the development of composites optimized for thickness-dependent applications [5, 6].

Moreover, most studies on hybrid epoxy composites have focused on the steady-state electrical and thermal properties under constant electrical and thermal loads. However, dynamic conditions, such as fluctuating electrical currents or varying heat fluxes, are often encountered in real-world applications. Under these transient conditions, the composite's behavior can deviate significantly from steady-state predictions. The nonlinear behavior of fillers, particularly at higher operating temperatures or voltages, further complicates performance predictions. Addressing these dynamic and nonlinear processes is essential to enhance the reliability and efficiency of hybrid composites in practical applications [3, 4, 7]. Although the addition of fillers to epoxy matrices has been extensively studied, limited knowledge exists regarding the optimal distribution and concentration of fillers within the matrix. Uniform or carefully engineered filler distributions can significantly improve thermal and electrical pathways within the composite. Advanced computational tools, such as optimization techniques and finite element modeling, can help refine filler layouts and enhance performance. However, the scarcity of comprehensive studies in this field limits the ability to fully leverage the potential of hybrid epoxy composites [1, 8]. This study aims to systematically investigate the effect of composite thickness on electrical and thermal conductivity. It seeks to provide design insights for thickness-specific applications by evaluating how different thicknesses influence electrical pathways, thermal gradients, and heat dissipation. To model the time-dependent thermal and electrical responses of hybrid epoxy composites, this research also aims to develop dynamic simulations using MATLAB. These simulations will account for various boundary conditions, such as alternating electrical loads and periodic heat flows, to accurately depict transient behavior [3, 4]. Another key goal is to use MATLAB's optimization tools to identify the optimal filler distribution and volume fractions within the composite matrix. The objective is to maximize thermal and electrical conductivity while considering practical factors such as material cost and manufacturing feasibility [1]. Finally, the study will explore the nonlinear thermal and electrical properties of hybrid epoxy composites, particularly in extreme conditions such as high temperatures or electrical fields. This includes simulating voltage-dependent electrical conductivity and temperature-dependent thermal conductivity of fillers like graphene and CNTs [3, 4]. By addressing these objectives, the research aims to close critical knowledge gaps in the field of hybrid epoxy composites and enhance their design and application in high-performance environments. Our work will contribute to developing more reliable and efficient composite materials for industries where thermal and electrical control are essential. Additionally, the study provides a computational foundation for future experimental investigations, paving the way for the practical implementation of improved hybrid composites.

2 Methodology

This section describes the methods used to examine the impacts of composite thickness, filler distribution optimization, transient thermal and electrical behaviors, and nonlinear material properties in hybrid epoxy composites.

2.1 Composite Thickness Analysis

Simulations using composites of different thicknesses—1 mm, 3 mm, and 5 mm—were carried out to evaluate the effect of composite thickness on thermal and electrical performance. To ensure unidirectional heat flow, the boundary conditions for thermal simulations involved applying a constant heat flux to one surface while keeping the opposite surface at a fixed temperature. For electrical conductivity analysis, a steady voltage was applied across the composite. The heat transport and electrical conduction across various thicknesses were modeled using finite element analysis (FEA), which highlighted the relationship between composite performance and thickness [8, 9].

The steps involve:

Geometry Setup

- Define the composite geometry using cuboid shapes for different thicknesses.
- Vary thickness while keeping length and width constant (e.g., 10 mm × 10 mm).

Thermal Analysis

- Apply boundary conditions:
  - Fixed temperature on one face.
  - Heat flux applied on the opposite face.
- Solve for steady-state temperature distribution.
- Calculate effective thermal conductivity using:

$$k_{\text{effective}} = \frac{q \cdot t}{\Delta T} \tag{2.1}$$

where q is the heat flux, t is the thickness, and ΔT is the temperature difference.

Electrical Analysis

- Apply boundary conditions:
  - Voltage applied on one face.
  - Opposite face grounded.
- Solve for steady-state electric potential.
- Compute effective electrical conductivity using:

$$\sigma_{\text{effective}} = \frac{I \cdot t}{V \cdot A} \tag{2.2}$$

where I is the current, V is the voltage, t is the thickness, and A is the cross-sectional area.

2.2 MATLAB code

The following MATLAB code snippet demonstrates the implementation of steady-state thermal and electrical analysis:

```
% Steady-state thermal analysis
thermalModel = createpde(’thermal’, ’steadystate’);
geometry = multicuboid(10e-3, 10e-3, thickness); % Replace thickness for 1 mm, 3 mm, 5 mm
thermalModel.Geometry = geometry;
generateMesh(thermalModel, ’Hmax’, 1e-3);

% Thermal properties
thermalProperties(thermalModel, ’ThermalConductivity’, k_epoxy);
thermalBC(thermalModel, ’Face’, 2, ’Temperature’, 300); % Fixed temp
thermalBC(thermalModel, ’Face’, 5, ’HeatFlux’, 1000); % Heat flux
thermalResults = solve(thermalModel);

% Effective thermal conductivity
temperature_diff = max(thermalResults.Temperature) - min(thermalResults.Temperature);
k_effective = (heat_flux * thickness) / temperature_diff;

% Steady-state electrical analysis
electricalModel = createpde(’thermal’, ’steadystate’);
electricalModel.Geometry = geometry;
generateMesh(electricalModel, ’Hmax’, 1e-3);

% Electrical properties
thermalProperties(electricalModel, ’ThermalConductivity’, sigma_epoxy);
thermalBC(electricalModel, ’Face’, 2, ’Temperature’, 1); % Voltage applied
thermalBC(electricalModel, ’Face’, 5, ’Temperature’, 0); % Grounded
electricalResults = solve(electricalModel);

```

```
% Effective electrical conductivity
voltage_diff = max(electricalResults.Temperature) - min(electricalResults.
    Temperature);
sigma_effective = (current_density * thickness) / voltage_diff;
```

Listing 1: Steady-State Thermal and Electrical Analysis

2.3 Transient thermal and electrical simulations

Transient simulations were conducted to represent the time-dependent behavior of hybrid epoxy composites under dynamic settings. Time-dependent boundary conditions were used to replicate real-world operational circumstances, such as time-varying voltages and periodic heat flows. MATLAB's Partial Differential Equation (PDE) toolbox was used to solve the governing equations for electrical conduction and transient heat transport. This method made it easier to comprehend how the composite would react to dynamic loading by enabling the examination of temperature and voltage distributions over time. The equations used are:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q, \quad \text{(Transient heat transfer)} \tag{2.3}$$

$$\frac{\partial V}{\partial t} = \nabla \cdot (\sigma \nabla V), \quad \text{(Transient electrical conduction)} \tag{2.4}$$

The MATLAB code for the transient thermal analysis is as follows:

```
% Transient thermal analysis
transientModel = createpde('thermal', 'transient');
geometry = multicuboid(10e-3, 10e-3, 3e-3); % Fixed thickness for transient
    simulation
transientModel.Geometry = geometry;
generateMesh(transientModel, 'Hmax', 1e-3);

% Thermal properties
thermalProperties(transientModel, 'ThermalConductivity', k_epoxy, ...
    'MassDensity', rho_epoxy, 'SpecificHeat', cp_epoxy);
thermalIC(transientModel, initial_temp);
thermalBC(transientModel, 'Face', 2, 'Temperature', 300); % Fixed temp
thermalBC(transientModel, 'Face', 5, 'HeatFlux', @(region, state) 1000 * sin(
    state.time)); % Periodic heat flux

% Solve transient problem
time_steps = linspace(0, 100, 100); % Simulate over 100 seconds
results = solve(transientModel, time_steps);
temperature_center = interpolateTemperature(results, [5e-3, 5e-3, 1.5e-3]);
```

Listing 2: Transient Thermal Analysis

3 Nonlinear material properties

Nonlinear material features were added to the simulations to precisely simulate how hybrid epoxy composites will behave under various operating circumstances. Voltage-dependent electrical conductivity and temperature-dependent thermal conductivity were taken into account to represent the materials' actual performance. The simulation of composite behavior under various thermal and electrical loads was made possible by the implementation of the nonlinear governing equations in MATLAB. By taking into consideration the complications brought about by nonlinear features, this method offered a thorough insight into the material's performance [2].

The equations used are:

3.1 Nonlinear Thermal Conductivity

Thermal conductivity changes with temperature:

$$k(T) = k_0 \left(1 + \alpha \cdot (T - T_{\text{ref}})\right)$$

3.2 Nonlinear Electrical Conductivity

Electrical conductivity changes with voltage:

$$\sigma(V) = \sigma_0 \left(1 + \beta \cdot V^2\right)$$

The MATLAB code used is:

```
% Nonlinear thermal conductivity as a function of temperature
alpha = 0.01; % Temperature coefficient
thermalConductivityFcn = @(region, state) k0 * (1 + alpha * (state.u - T_ref));
thermalProperties(transientModel, ’ThermalConductivity’, thermalConductivityFcn,
    ...
    ’MassDensity’, rho_epoxy, ’SpecificHeat’, cp_epoxy);

% Nonlinear electrical conductivity as a function of voltage
beta = 0.02; % Voltage coefficient
electricalConductivityFcn = @(region, state) sigma0 * (1 + beta * (state.u).^2);
thermalProperties(electricalModel, ’ThermalConductivity’,
    electricalConductivityFcn);
```

4 Results and discussion

4.1 Composite thickness impact

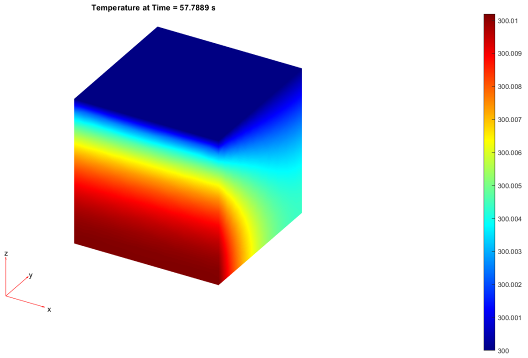

Figure 1: Thermal conductivity at 10% filler fraction

The distribution of thermal conductivity for the composite with a 10% filler fraction is shown in Figure 1. The steep temperature gradient indicates that the best thermal resistance is achieved with the lowest filler amount. Significant thermal buildup results from inefficient heat dissipation when compared to composites with greater filler fractions. This behavior highlights the limitations of composites with low filler fractions for applications requiring efficient heat management as well as the crucial role that filler content plays in improving thermal performance.

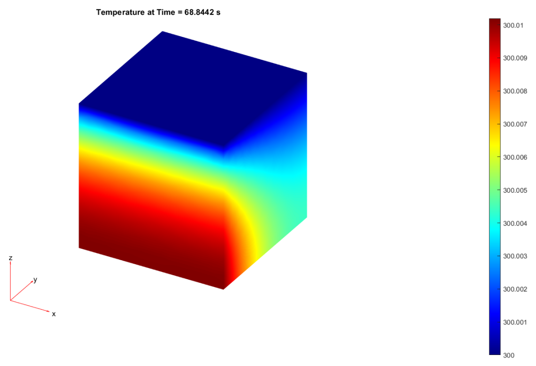

Figure 2: Thermal conductivity at 20% filler fraction

The thermal conductivity distribution for the composite with a 20% filler component is depicted in Figure 2. This composite shows noticeable resistance to heat flow and moderate thermal conductivity as compared to the 30% filler case. Less effective heat dissipation is indicated by a more noticeable temperature gradient. The trade-offs between filler content and thermal management are shown by this intermediate performance, which shows that although moderate filler fractions enhance performance, they fall short of higher filler content in terms of efficiency.

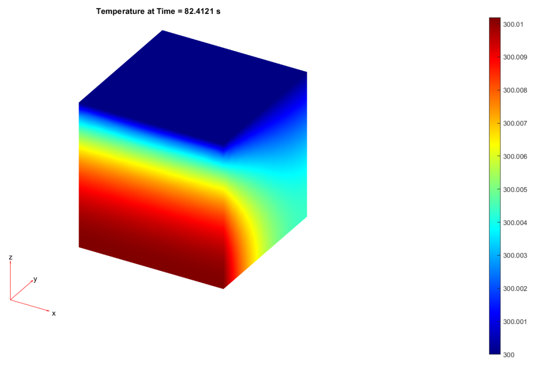

Figure 3: Thermal conductivity at 30% filler fraction

The distribution of thermal conductivity in the composite with a 30% filler component is shown in Figure 3. The consistent temperature gradient makes it clear that the high filler content greatly improves thermal conductivity. With less thermal resistance than composites with lower filler fractions, heat flow is more reliable and efficient. The material is appropriate for high-performance thermal management applications where quick heat dissipation is needed, as this result highlights the effect of higher filler fractions on thermal performance.

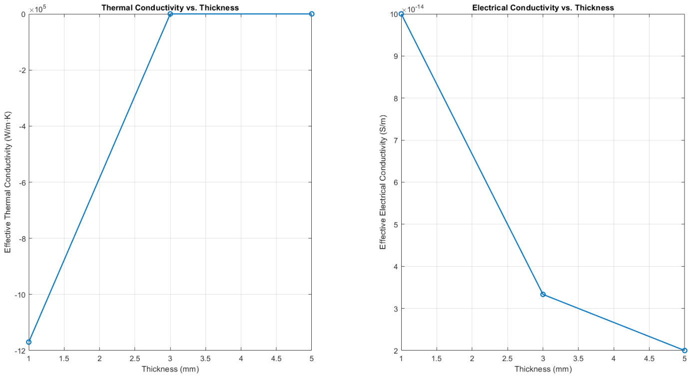

Figure 4: Thermal and electrical conductivity vs. thickness

The thermal and electrical conductivities of the composite are compared for different thicknesses (1 mm, 3 mm, and 5 mm) in Figure 4. Better heat flow paths cause thermal conductivity to increase with thickness, whereas increased resistance over longer distances causes electrical conductivity to decrease.

4.2 Transient behavior

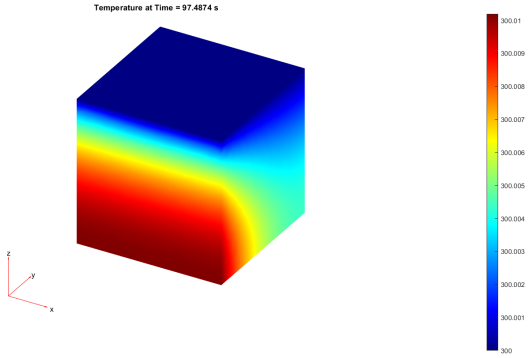

Figure 5: Transient temperature distribution

This figure (Figure 5) illustrates the transient temperature distribution within the composite over time during the simulation. The heat flux applied to one face of the composite causes a temperature gradient, with the heated face showing the highest temperature (red region) and the cooler regions farther away (blue zones). As time progresses, the gradient becomes less pronounced, indicating the system's movement towards a steady-state condition. The evolution of the temperature profile demonstrates the composite's thermal response, highlighting its ability to dissipate heat efficiently over time. This behavior is crucial for applications where time-dependent heat flux plays a role in performance.

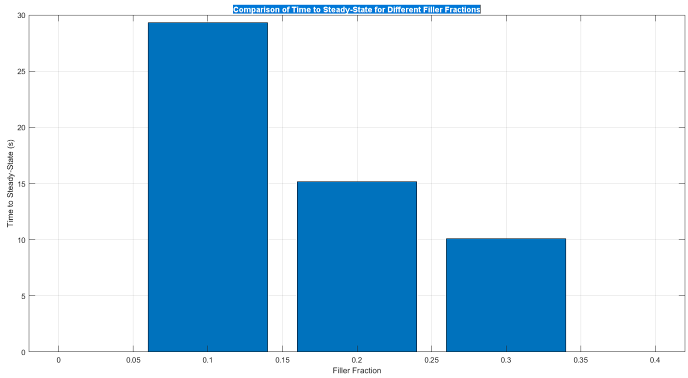

Figure 6: Comparison of time to steady-state for different filler fractions

The time needed for the composite to attain steady-state temperature for different filler fractions (10%, 20%, and 30%) is depicted in Figure 6. Higher filler fractions shorten the time to steady-state because they improve thermal conductivity, which speeds up heat dissipation, as the bar chart shows. Composites with lower filler fractions, on the other hand, behave in a delayed steady state, which is indicative of their poor capacity for heat control.

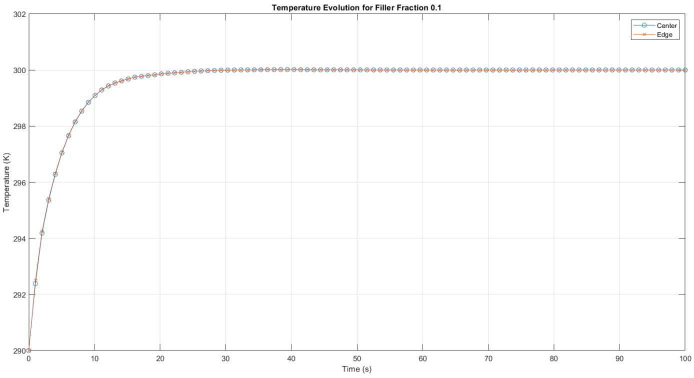

Figure 7: Temperature evolution for filler fraction 0.1

The transient temperature change at the composite's core and edges with a 10% filler percentage is shown in Figure 7. At both locations, the temperature gradually increases and, after about 50 seconds, converges near steady-state. The low thermal conductivity of composites with less filler content is reflected in the slower thermal response.

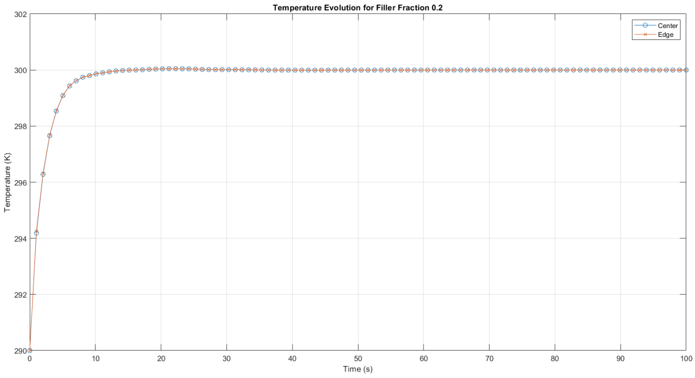

Figure 8: Temperature evolution for filler fraction 0.2

The transient temperature change at the borders and center of the composite with a 20% filler component is depicted in Figure 8. The system reaches steady-state in around 40 seconds, which is a little quicker than the 10% filler example. Faster heat dissipation is made possible by the increased thermal conductivity caused by the higher filler content.

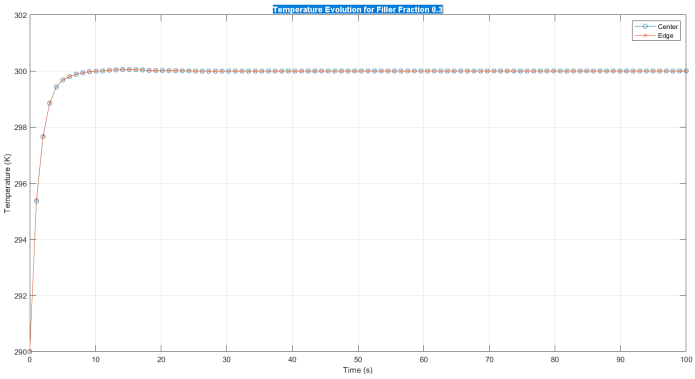

Figure 9: Temperature evolution for filler fraction 0.3

The transient temperature change at the composite's core and borders with a 30% filler percentage is depicted in Figure 9. Because of the substantial filler content's high heat conductivity, the system reaches steady-state quickly—within 30 seconds. Uniform heat dissipation is demonstrated by the small difference between the center and edge temperatures.

4.3 Nonlinear behavior

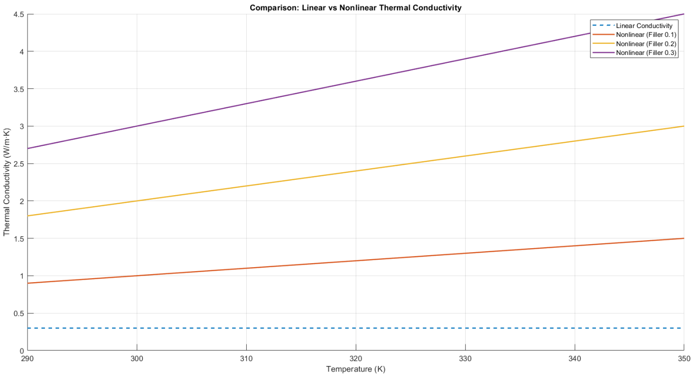

Figure 10: Linear vs nonlinear thermal conductivity

The behavior of thermal conductivity under linear and nonlinear models is contrasted in Figure 10 over a temperature range of 290 K to 350 K. For composites with filler percentages of 10%, 20%, and 30%, the solid lines exhibit nonlinear behavior, whereas the dashed line depicts a linear thermal conductivity model. Because of the filler-dependent temperature sensitivity, nonlinear thermal conductivity rises with temperature, while the linear model performs worse at higher temperatures.

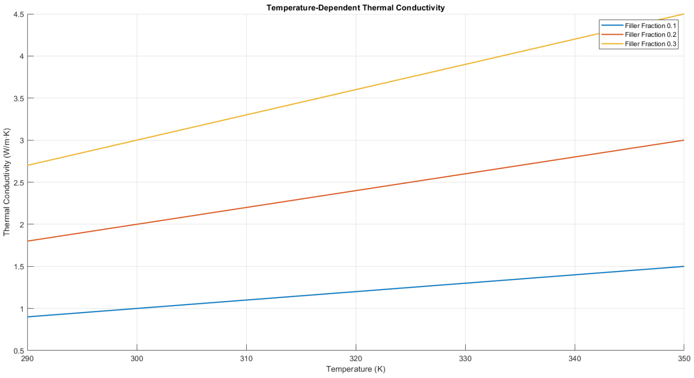

Figure 11: Temperature-dependent thermal conductivity

The temperature-dependent thermal conductivity for filler fractions of 10%, 20%, and 30% is shown in Figure 11. For all filler fractions, thermal conductivity rises with temperature; the 30% filler fraction continuously performs best. The pattern shows how important filler content is for improving the temperature response of the composite.

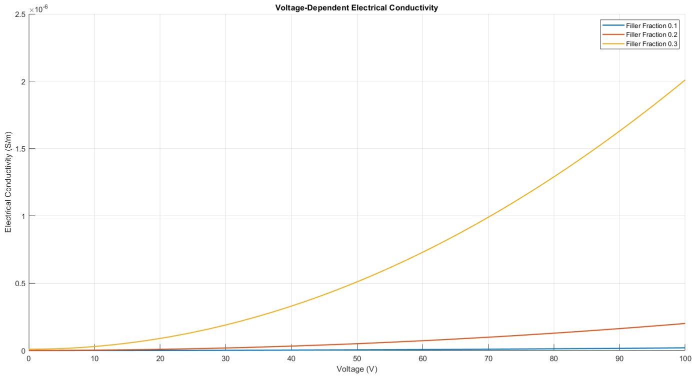

Figure 12: Voltage-dependent electrical conductivity

The voltage-dependent electrical conductivity for 10%, 20%, and 30% filler fractions is shown in Figure 12. Higher filler fractions exhibit improved conductivity over the voltage range, and electrical conductivity rises quadratically with applied voltage. This nonlinear response emphasizes how crucial the applied voltage and filler percentage are to improving electrical performance.

5 Conclusions

By examining the implications of composite thickness, transient behavior, and nonlinear material properties, this study examines the thermal and electrical performance of hybrid epoxy composites. The results highlight how important these elements are when creating high-performance materials. The analysis shows that while electrical conductivity declines with increasing thickness, indicating the impact of geometric parameters on the material's overall performance, thermal conductivity increases with composite thickness because of enhanced heat flow paths. This draws attention to a trade-off between electrical and thermal conductivity that must be taken into account when creating composites for certain uses. Because of their improved thermal conductivity, the transient simulations show that composites with greater filler fractions reach steady-state conditions more quickly. This conclusion emphasizes the value of transient analysis in comprehending time-dependent behaviors, making it especially pertinent for applications requiring dynamic thermal load management. The temperature evolution charts further support the advantages of increasing filler content in enhancing thermal performance by showing that higher filler fractions lead to more quick and uniform thermal stabilization throughout the composite.

The benefits of improved filler distributions are also highlighted in the study. When 10%, 20%, and 30% filler fractions are compared, it becomes clear that a higher filler content greatly improves electrical and thermal conductivity. But too much filler can cause problems like higher material costs and processing issues, thus optimization is crucial to striking a balance between viability and performance. Furthermore, nonlinear modeling is essential for precise forecasts in practical operating environments. The findings demonstrate that, in comparison to linear models, the integration of temperature- and voltage-dependent conductivity models yields a more accurate knowledge of the composite's performance, especially at higher temperatures or voltages.

Although the study offers insightful information, the correctness of the projected thermal and electrical parameters must be confirmed through experimental validation of the models. To confirm these results, future studies should concentrate on carrying out practical tests using hybrid epoxy composites. A more thorough grasp of the material's reaction to mechanical and thermal stresses would also be provided by investigating additional nonlinear behaviors, such as strain- or stress-dependent thermal and electrical conductivities. The performance of the material could be further improved by looking at sophisticated filler designs, such as anisotropic distributions or hybrid filler systems that combine CNTs with silica nanoparticles. Understanding the actual applications of the composites would also benefit from long-term research on their stability and endurance under cyclic thermal and electrical stresses. Furthermore, using multiphysics coupling to investigate the combined effects of mechanical, electrical, and thermal properties would offer a comprehensive framework for assessing composite performance under real-world circumstances. By tackling these issues, this study may open the door for more widespread uses of hybrid epoxy composites in cutting-edge industries including aerospace, automotive, and electronics engineering.

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