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SIZE EFFECT OF THERMAL CONDUCTIVITY IN HETEROGENEOUS MEDIA

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The analysis of thermal energy distribution within composite architectures reinforced with discrete particulate inclusions represents a rigorous and formidable scientific challenge. This complexity originates primarily from the exceedingly intricate multi-scale interactions occurring between filler particles of diverse geometries and the surrounding matrix phase, particularly when subjected to transient heat transfer conditions. Unlike conventional homogeneous materials, particulate-reinforced composites often demonstrate complex orthotropic or entirely anisotropic thermal behaviors, which fundamentally reconfigure the underlying mechanisms of energy dissipation and storage within the material volume. The development of a robust computational methodology capable of accurately describing heat propagation in these heterogeneous systems is significantly hindered by the existence of extreme local gradients in thermal conductivity and specific heat capacity at the phase interfaces. These interfacial regions, characterized by high thermal contact resistance and distinct physical properties, create sharp discontinuities in the temperature field that are difficult to capture using standard analytical or numerical techniques without incurring prohibitive computational costs. Furthermore, the stochastic nature of particle distribution, varying aspect ratios, and the potential for clustering add layers of complexity to the mathematical formulation of the problem [1]. Modern industrial applications, ranging from high-power microelectronics packaging to advanced aerospace structural components, increasingly rely on these materials for their highly tailored thermal properties, yet the lack of precise predictive models remains a critical bottleneck in the material design process. Non-stationary processes introduce additional temporal dependencies where the rate of heat penetration is governed by the effective thermal diffusivity, which is itself a complex function of the local morphology and phase interaction. Traditional approaches based on the classical Fourier heat conduction law often fail to provide reliable results in scenarios involving high-frequency thermal loading or extremely small spatial scales, where the discrete nature of the filler becomes dominant and micro-scale transport phenomena must be considered. The mismatch between the matrix and filler properties leads to localized thermal stresses and potential degradation of the composites.

The numerical analysis reveals a significant phenomenon regarding the indexing matrix elements, which exhibit a remarkably negligible dependence on the temporal variable throughout the transient phase. This observed stability is fundamentally attributed to the mathematical properties of the chosen wavelet basis, specifically the existence of vanishing moments that effectively neutralize the low-frequency polynomial components inherent in the macro-scale temperature field [2]. By selectively isolating the high-frequency fluctuations that are intrinsically linked to the composite's heterogeneous microstructure, the wavelet-based algorithm concentrates exclusively on the singular features of the local thermal gradient. As a result, the developed computational framework maintains a high level of operational efficiency even during extended transient simulations, as the fundamental indexing structure remains invariant and does not necessitate periodic re-computation or updating. This localized spectral filtering property represents a substantial advancement over traditional global transformation methods, which often encounter difficulties in distinguishing between steady background temperature increments and the localized effects occurring at the phase interfaces.

Moreover, the systematic decomposition of the indicator matrix in accordance with the spatial vector field components of the inclusions proves to be an indispensable factor in the accurate characterization of heat transfer within architectures defined by a high-volume fraction of particulate fillers. In such congested systems, the close proximity of adjacent particles triggers complex multi-body interactions that fundamentally alter the effective thermal pathways. The data further indicate that an increase in the dispersity of the polymodal filler fraction results in a pronounced distortion of the scalar field components of the effective thermal conductivity. This phenomenon is particularly emphasized along the axis of the primary temperature gradient imposed on the external boundaries of the composite specimen. The heightened variation in the size distribution of the particles induces a more tortuous trajectory for heat conduction, giving rise to localized thermal concentrations or hot spots and corresponding shadow zones. These fine-scale features represent significant deviations from the mean-field predictions and remain largely undetectable by conventional homogenized

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analytical models, which tend to overlook the discrete nature of the heat flux distribution in highly dispersed media.

Summary and conclusions. The application of multiscale domain partitioning within this framework demonstrates the clear advantages of wavelet methods in resolving the complexities of thermal diffusion. Whereas global transforms provide only a broad overview, wavelet-based techniques capture the subtle diffusion patterns at sub-particle scales with exceptional fidelity.

Our findings confirm that this methodology yields superior resolution and a more authentic physical representation of heat transport in heterogeneous media. This precision enables a deeper understanding of how filler morphology dictates macroscopic thermal behavior, offering a robust path for developing next-generation composite materials with precisely engineered thermal characteristics.

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