THERMAL ANALYSIS OF A PAM–SiO_2 POLYMERIC COMPOSITE PANEL USING COMSOL MULTIPHYSICS

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Abstract

Polymeric composites offer an ideal combination of lightweight design, easily modified electrical, mechanical, and thermal properties, and accessible processing techniques. These properties make them very attractive and suitable for advanced and energy-efficient applications. Integrating them into solar panel structures or thermally insulated panel structures can enhance thermal control and mechanical properties while offering a sustainable and cost-effective production process.

This study investigates the thermal behavior of a multilayer panel containing PAM–SiO_2 polymeric composite as an insulation layer. COMSOL Multiphysics is used to perform transient thermal simulations with a parametric sweep of the composite's effective thermal conductivity (k_eff). The influence of filler content, temperature change, through-thickness thermal gradients, and heat flux distribution was analyzed under continuous heat loading.

The results demonstrate the thermal insulation capabilities of PAM–SiO_2 composites and their potential for applications in thermally regulated structures such as smart panels, protection barriers, and electronic packaging.

Keywords: *polymeric composite, thermal analysis, panel, PAM–SiO_2*

INTRODUCTION

Polymeric composites are increasingly used in thermal insulation systems due to their low density, tunable thermal conductivity, and compatibility with scalable processing methods. These materials obtain improved thermal stability and adjustable conductivity qualities that make them suitable for applications requiring both regulated dissipation and energy retention when supplemented with fillers like silica (SiO_2). Because of the interface synergy between the hydrophilic PAM matrix and the thermally resistant SiO_2 filler, polyacrylamide (PAM)–SiO_2 composites in particular show interesting properties in thermal barrier design. The quality of the matrix–filler interface, which controls phonon transport between phases and consequently influences thermal conductivity, is linked to the filler's efficacy in addition to its volume fraction (Wang et al., 2019; Cui et al., 2011).

A PAM–SiO_2 polymeric composite layer is especially useful for integrating into panel designs because it combines the flexibility and low heat conductivity of PAM with the filler-driven tunability and thermal stability of SiO_2. The composite is a good option for insulating layers in multilayer thermal systems because of its synergy, which permits controlled heat transport.

They show thermal degradation onset near 196 °C, indicating good thermal endurance for moderate heat applications (Wang et al., 2019). In similar systems, even low filler content significantly improves conductivity, with up to 67% increase in epoxy/MWCNT@SiO_2 composites (Cui et al., 2011). In amorphous polymers like PAM, phonon scattering from filler dispersion and interfacial mismatch limits thermal transport (Fraleoni-Morgera & Chhikara, 2019).

A numerical study of the PAM–SiO_2 composite panel's heat response using COMSOL Multiphysics is presented in the following sections. Through thickness temperature distribution, temperature evolution over time, and the impact of changing effective thermal conductivity on the overall insulating performance of the panel are examined.

MATERIALS AND METHODS

Panel Structure

The structure of the panel is simulated using COMSOL Multiphysics. It consists of a multilayer panel modeled in two dimensions (2D). The panel is represented by a simplified model consisting of three primary layers within a 5.5 mm thickness: a central 3.5 mm PAM–SiO_2 composite sandwiched between a 1 mm silicon top layer for heat absorption and a 1 mm glass bottom layer for structural support.

The focus of this study is the middle layer. It is a thermally responsive polymeric composite based on polyacrylamide (PAM) and modified with silica (SiO_2). PAM was selected due to its hydrophilic nature, low intrinsic thermal conductivity (~0.2 W/m·K), and compatibility with various fillers. SiO_2 is frequently used in polymer nanocomposites to improve mechanical integrity, interfacial adhesion, and thermal resistance.

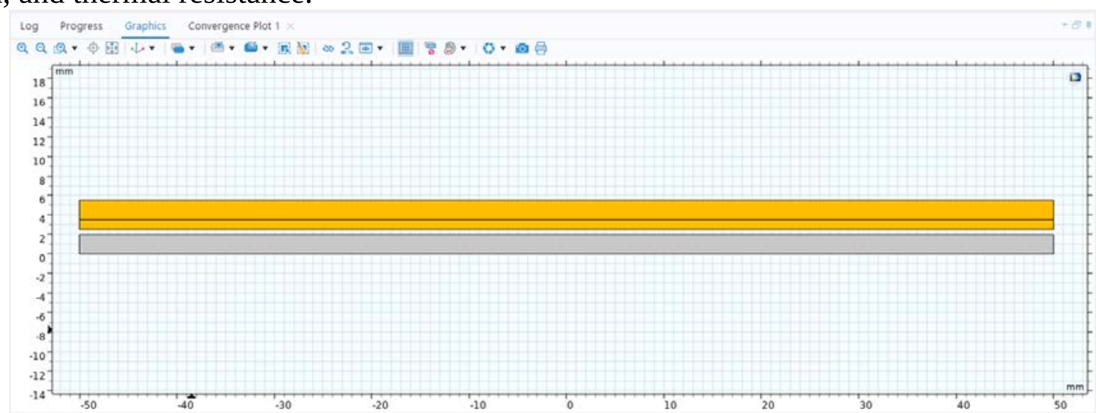

Fig 1. Panel represented from a rectangular 2D cross-section

This layering strategy reflects approaches used in multilayer thermal insulation systems, where a functional composite core is sandwiched between structural and thermally active outer layers to balance mechanical and thermal performance (Hwang et al., 2024).

COMSOL Setup

COMSOL Multiphysics® was used to assess the multilayer panel's thermal performance under transient settings using the Heat Transfer in Solids physics interface. (COMSOL, 2021).

The system's thermal evolution under constant heating was represented by a simulation time range of 0 to 600 seconds. The three layers—silicon, PAM-SiO_2 composite, and glass—were each characterized as distinct domains in the geometry. A structured mesh was applied with refined components concentrated across the polymeric composite region and close to the interfaces.

Boundary conditions were applied as follows:

- A **constant heat flux** was applied on the **top boundary** to simulate a continuous and uniform thermal load. (COMSOL, 2021).
- A convective cooling boundary was defined on the bottom side, using a convective heat transfer coefficient h to simulate natural heat exchange with the surrounding environment. (Khalifa, 2001).

Parametric Study of Composite

The influence of filler content on thermal performance is evaluated using a parametric sweep in COMSOL. The effective thermal conductivity (k_eff) of the composite layer varies in the selected conductivities 0.25, 0.35, 0.45, and 0.55 W/(m·K), representing progressive increases in SiO_2 filler concentration within the PAM matrix aligning with the ones reported in the literature for polymer composites containing inorganic fillers like silica (Zhang, Deng, & Fu, 2018).

RESULTS AND DISCUSSION

Maximum Surface Temperature vs. k_{eff}

The parametric study's findings demonstrate an inverse relationship between the maximum surface temperature attained during simulation and the composite layer's thermal conductivity. The panel's capacity to disperse heat improves with an increase in effective thermal conductivity, which lowers the surface temperature after the 600-second simulation.

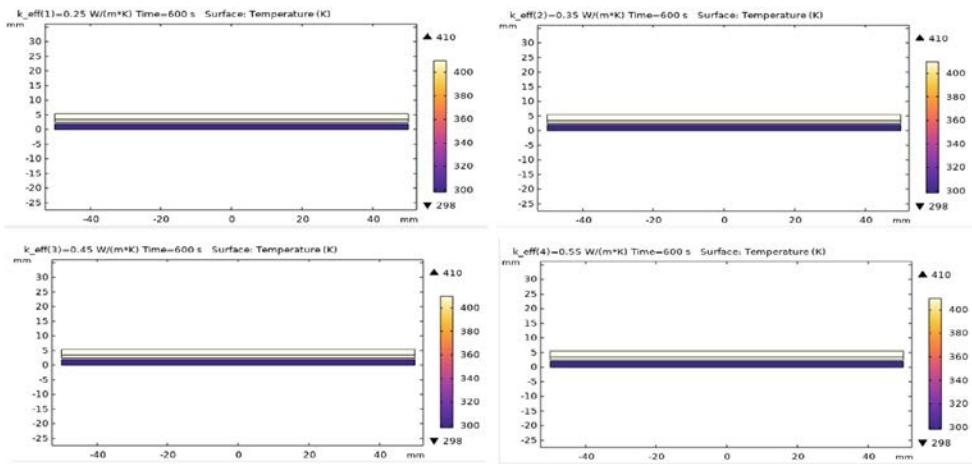

Figure 2. Thermal performance under different effective thermal conductivity (k_eff)

This behavior supports the hypothesis that lower-conductivity composites are more effective as thermal insulators, as they retain more heat and restrict heat flow through the panel structure.

Temperature Rise (ΔT) Over Time

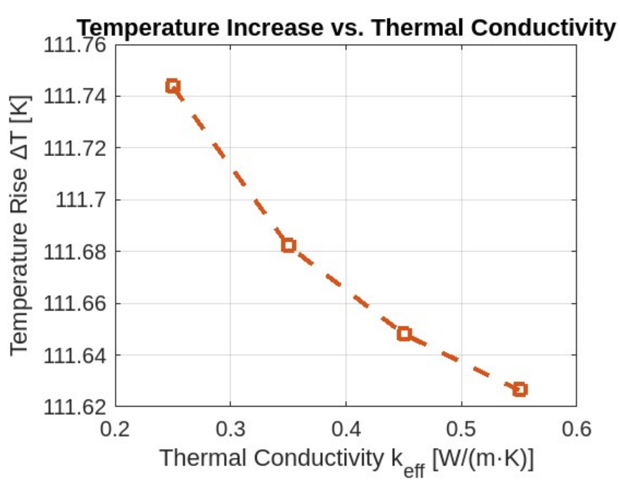

Figure 3. Temperature rise at the surface of the composite panel after 600 seconds of continuous heating, plotted against varying effective thermal conductivity k_eff.

The temperature increase (ΔT) was evaluated between 0 and 600 seconds to evaluate thermal durability. As shown in Figure 3, lower thermal conductivity values (e.g., 0.25 W/(m·K)) resulted in higher ΔT. This indicates stronger insulation behavior. On the other hand, higher k_eff values led to reduced temperature rise due to better heat dissipation. This confirms the tunability of PAM–SiO_2 composites for insulation applications depending on filler content (Cui et al., 2011; Wang et al., 2019).

Transient Thermal Evolution

Figure 4 shows the transient thermal evolution of the composite panel over a 600-second simulation period, based on varying effective thermal conductivity values.The data were exported from COMSOL and post-processed in MATLAB to enhance visualization. These results reinforce the trade-off between insulation and thermal spread when tuning composite properties.

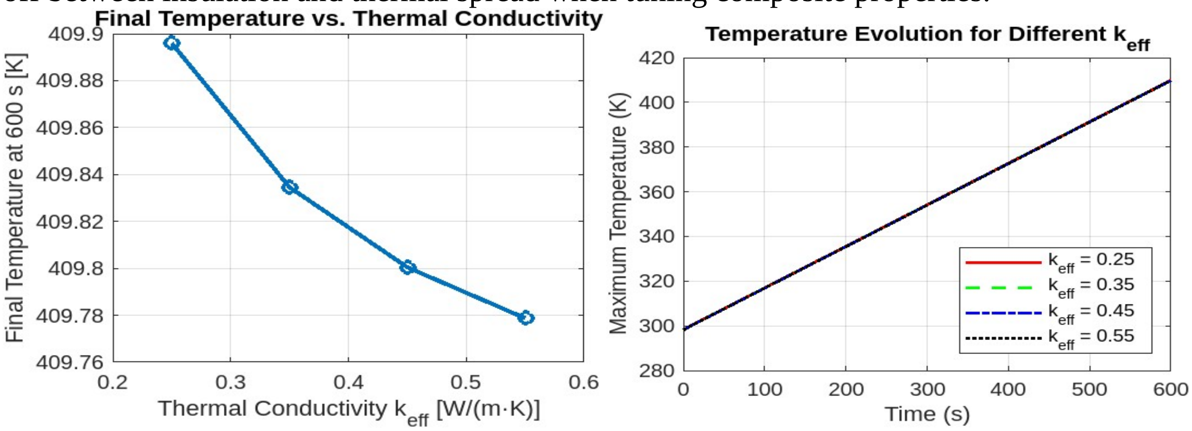

Figure 4. Final Temperature vs. Thermal Conductivity and Temperature Evolution Over Time for Different k_eff

Through-Thickness Temperature Profile

A vertical cut-line analysis was performed across the full panel thickness (0–5.5 mm) to evaluate the internal temperature gradient at t=600 s for each k_eff , highlighting the thermal behavior of individual layers.

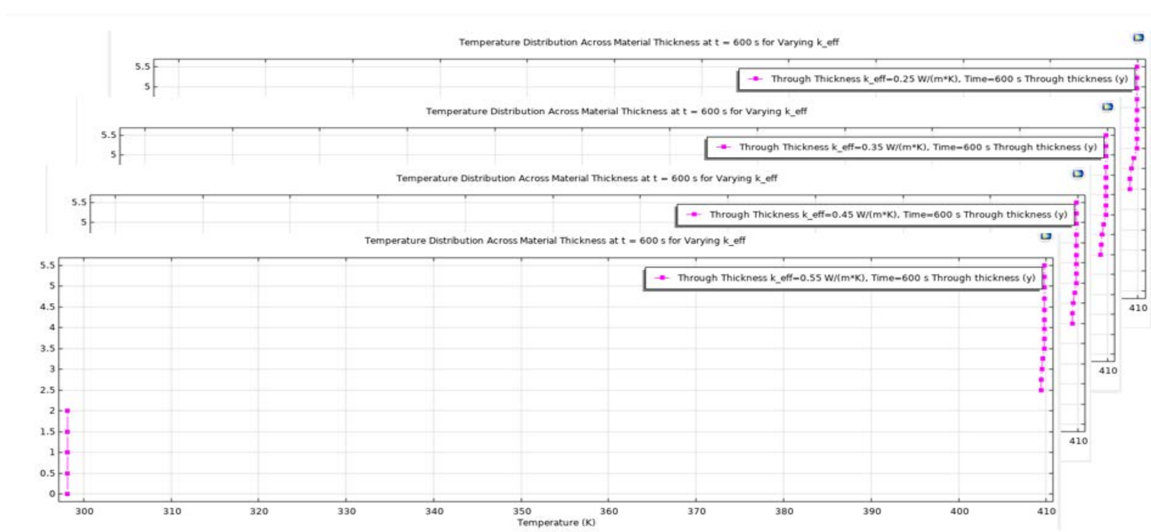

Figure 5. Temperature distribution across the material thickness for different keff at t = 600 s.

This figure illustrates the temperature distribution across the panel thickness for different thermal conductivity values. For k_eff=0.25 W/m·K, a steep gradient is observed, indicating poor heat diffusion and strong thermal resistance within the PAM–SiO_2 layer. As k_eff increases to 0.35 and 0.45 W/m·K, the temperature profile becomes more gradual, reflecting improved thermal conduction. At the highest k_eff value, the distribution appears nearly linear, showing uniform heat flow from the top to the bottom surface. This behavior confirms that the composite can be used for either insulation or dissipation applications, depending on its conductivity.

Interface Behavior

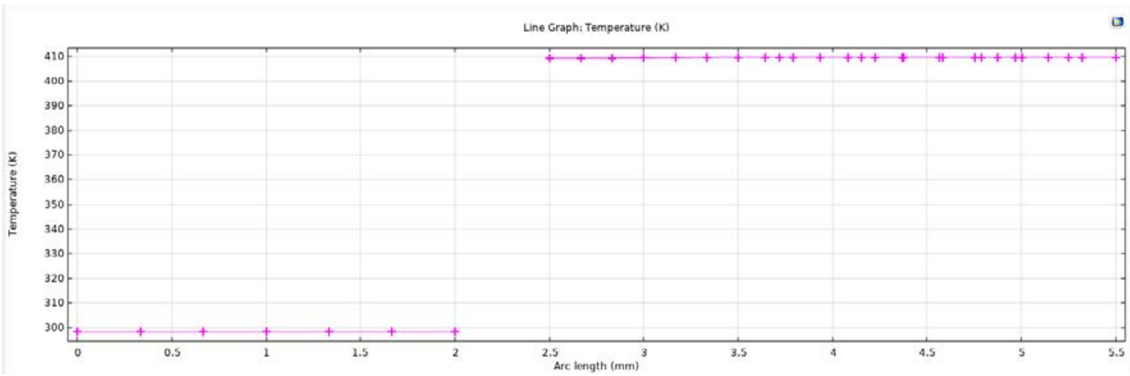

Figure 6. Temperature distribution along the arc length at t = 600 s for a panel subjected to heating from the top surface.

The plot illustrates the temperature profile along the arc length of the sample, traversing through multiple material layers. The first region (0–2 mm) exhibits a constant temperature near 298 K, indicating a layer with low thermal conductivity that resists temperature rise, likely a glass substrate or low-conductivity PAM base. Around 2–2.5 mm, a sharp temperature increase is observed, marking the interface between layers. Beyond 2.5 mm, the temperature stabilizes around 409 K, corresponding to the top material layer, which is thermally loaded and has higher thermal conductivity.

This clear stepwise temperature change demonstrates:

- Strong thermal resistance at the material interface
- Distinct thermal behavior across the composite thickness
- Effective insulation of the bottom layer

CONCLUSION

The study shows that PAM–SiO_2 polymeric composites have tunable thermal behavior suitable for multilayer insulation systems. The material can function as a strong insulator or a moderate thermal spreader, depending on how effective thermal conductivity is set. Lower conductivity allows for better heat retention, while higher conductivity allows for better heat dissipation. That enables designers to adapt the same composite formulation for different applications. It was also seen that layer thickness and material selection play a crucial role in terms of energy retention and heat distribution, based on earlier studies involving epoxy composites (Qamili & Hoxha, 2025).

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