# Exploring the Role of Nanomaterials in Advancing Solar Thermal Technologies

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## ABSTRACT

Photovoltaics (PV) are a viable renewable energy technology, yet inadequate conversion efficiency remains a steadfast problem. A heat extractor that will attach to the back of a PV panel will cool it and boost its power output. While thermoplastics are found to be better overall materials than metals due to low density and environmental resistance, they fall short in thermal conductivity. This work explores various composite materials and fabrication methods to close the gap in thermal conductivity between thermoplastics and metals. Graphene nanoparticles and carbon nanotubes are found to be effective additives to improve the thermal conductivities of base polymers. In this paper, the significance of alignment of carbon-based fillers within a polymer matrix is established and the advantages and drawbacks of various alignment methods are discussed. Finally, the environmental impacts that high thermal conductivity polymer composites have are considered.

***Keywords:*** *heat recovery, thermal conductivity, polymers, carbon-based additives, solar PV, Solar Thermal*

## 1 INTRODUCTION

Photovoltaic (PV) technology continues to face limitations in efficiency. At standard test condition of 25°C, common PV panels convert less than 21% of incoming solar energy into electricity, and this conversion efficiency decreases as panels heat up during the day. With PV panel surface temperatures reaching 70°C, conversion efficiency drops to 16% or lower. In addition, increased operating temperatures create a greater fatigue, increasing the rate at which panels must be scrapped or replaced and therefore decreasing PV panel lifetime and panel lifetime energy output.

To lower PV panel temperatures, a heat extractor can be attached to the back of PV panels. The extractor allows cold fluid to flow uniformly across the back of the PV panel, cooling it and absorbing the heat in the process. The extractor covers the panel sub-surface and contains features to create turbulence to maximize heat transfer while maintaining uniform flow for uniform cooling. The opposite side in contact with the PV panel is completely flat, enabling increased contact for maximum heat transfer.

An effective way to improve heat transfer is to incorporate more thermally conductive composite materials as an interface between the PV panel and the extractor fluid. The interface can be selected from a lightweight thermoformed polymer. Two of the most widely available plastics are high-density polyethylene (HDPE) and low-density polyethylene (LDPE). HDPE is not suitable for this application due to its low thermal conductivity of 0.52 W/m-K, and an operating temperature of 70°C, which is lower than required standard working temperature of 80 °C. LDPE has a higher working temperature of 85 °C but has a lower thermal conductivity of 0.3 W/m-K which is inadequate for this application.

Embedding polymers with additives such as carbon-based nanoparticles, metal filaments or ceramics has the potential to improve the thermal conductivity of heat extractors by many orders of magnitude. Carbon-based nanoparticles are among the most thermally conductive additives. Studies have shown that graphite LDPE polymer composites with ratios such as 60wt% graphite/40wt% LDPE are up to 23 times more thermally conductive than that of pure LDPE. Additionally, these composites increase the structural strength of a polymer, leading to higher environmental resistance and longer lasting application.

This paper will investigate various compositions of additives as well as the role alignment plays in the optimization of energy harvesting, particularly in solar waste heat applications. These materials will be analyzed based on ease of scalability, improvement in thermal conductivity, resistance to the environment and cost. The main objective of this paper is to determine the most suitable composite materials for PV thermal applications.

## 2 EXTRACTOR MATERIALS

In this application, each material must be analyzed based on their thermal conductivity ($k$), coefficient of linear thermal expansion ($\alpha$) and density ($\rho$). Ensuring high $k$ value (W $m^{-1}$ $K^{-1}$) will maximize the thermal efficiency of the heat extractors. The value of $\alpha$ ($10^{-6}$ °$C^{-1}$) is important because materials that expand at different rates, due to delamination and debonding effects, may result in structural defects to the components over time. Table 1 compares these parameters for suitable materials. Although metals such as aluminum and copper possess high thermal conductivity, their density is high, making them non-ideal. This shifts the focus to thermoplastic polymers such as polypropylene, ABS, polyethylene and polycarbonate. Among these, polypropylene and LDPE stand out with their low density. These thermoplastics are also attractive due to their non-hygroscopic nature and low cost. The primary flaw of all these polymers is their heat transfer coefficient; it is approximately 3 orders of magnitude smaller than that of metals.

| Material | $k$, W $m^{-1}$ $K^{-1}$ | $\alpha$, $10^{-6}$ °$C^{-1}$ | $\rho$, g $cm^{-3}$ |
|---|---|---|---|
| Cu | 386 | 16.7 | 8.96 |
| Al | 239 | 21-24 | 2.7 |
| PP | 0.20-0.40 | 65-160 | 0.89-1.84 |
| LDPE | 0.33 | 175 | 0.91-0.94 |
| PC | 0.17-0.21 | 65-70.2 | 1.18-1.26 |
| ABS | 0.13-0.19 | 72-108 | 0.88-3.50 |
| Nylon-6 | 0.23-0.32 | 80 | 1.07-1.29 |

**Table 1:** Summary of potential extractor materials, thermal properties and density

Neither thermally conductive metals nor commercial thermoplastic polymers are adequate solutions for PV heat extraction application. From the two, thermoplastics are more economically viable, and their heat transfer abilities can be improved through appropriate additives. Carbon based materials including diamond, graphene nanoparticles (GnPs) and single/multi walled carbon nanotubes (SWCNT/MWCNT) are among the most thermally conductive materials on earth and have the potential to improve thermal conductivity of heat extractors if fabricated properly. Table 2 compares the thermal conductivities of carbon-based particles that are filler candidates in our application. Additionally, thermal boundary resistance, TBR ($m^2$ K $W^{-1}$) between the filler and the polymer is considered. The lower this value, the higher thermal conductivity the composite will have [1]. Two materials that stand out are GnPs and CNTs. With their heat transfer coefficient about five orders of magnitude larger than that of polymers and their low TBR value, the addition of these two nano-scale materials into polymers is a promising method for improving overall thermal conductivity.

| Material | $k$, W $m^{-1}$ $K^{-1}$ | $\alpha$, $10^{-6}$ °$C^{-1}$ | TBR [1] |
|---|---|---|---|
| Diamond | 2200 | 0.8 | - |
| Graphite nP | 470 | 4-8 | - |
| GnP | 4000 | ~ -3 to -8 | $10^{-9}$ |
| SWCNT | 3500 | - | $10^{-8}$-$10^{-7}$ |
| MWCNT | 2586 | - | $10^{-8}$-$10^{-7}$ |

**Table 2:** Summary of various materials comparing thermal properties sufficient to heat extractor application

## 3 FABRICATION

Random distribution of high-$k$ materials has been demonstrated to increase the $k$ value of the resulting composite polymer. Additional improvement can be achieved by aligning the high-$k$ materials to create thermal pathways. Even an incomplete pathway will increase the ability of heat exchangers to remove heat from the panel by lowering the resistance that heat transferring through the material experiences for a given portion of the extractor [2].

Furthermore, the orientation of certain materials within the polymer matrix can greatly alter thermal conductivity. For example, alignment, even if not a continuous pathway, is essential for graphene where its high in-plane $k$-value reaches up to 5000 W $m^{-1}$ $K^{-1}$, yet its out-of-plane thermal conductivity is only approximately 10-20 W $m^{-1}$ $K^{-1}$ [1]. Aligned pathways stretching between two conducting faces can lead to thermal conductivities up to 300% higher than the randomly distributed alternative with the percentage highly dependent on fabrication methods and concentration of filler materials [1].

A few potential fabrication methods are discussed below; all of which possess their own advantages and drawbacks within a heat extractor application.

### 3.1 Mechanical Densification of CNTs

Previous studies have shown that CNTs have the potential to greatly improve thermal conductivity of a base polymer through the method of mechanical densification and aligning carbon nanotubes. In one study by Marconnet et al., this method was shown to improve the $k$ value of a polymer by a factor of approximately 18 (16.7 vol% CNT) [3]. To achieve mechanical alignment, initially, MWCNTs are grown using chemical vapor deposition. Then their volume fraction is increased through mechanical densification, which is a process that also ensures alignment. The resulting material can then be filled with a polymer in fluid or glass transition state [4].

This method poses some challenges as in order to achieve high levels of thermal conductivity the CNT must be densely aligned (about 17 by volume or more for significant change) [3]. Additionally, this method was shown to create defective MWCNTs with even higher than expected levels of defects in production environments. These are two of many scalability issues that will be difficult to overcome in the near future.

### 3.2 Magnetic Field Alignment

The distribution of the thermally conductive filling could be performed through the usage of a magnetic field of sufficient strength. This would require an inserted filling that is magnetic (i.e., iron, nickel, etc.), but which will not interact negatively with the fluid flowing through the panel or the outside environment. Iron would likely experience oxidation when used in wet environments, damaging the structural integrity of the extractor panel and contaminating the fluid. Other magnetic metals such as nickel or cobalt don't have high enough thermal conductivities to make a sufficient impact. To combat this, Yan et al. explored the magnetic field alignment of GnP functionalized iron oxide, GnP-Fe3O4, within epoxy. It was found that with this alignment, a 40% improvement to thermal conductivity compared to random distribution was achieved [2].

### 3.3 Electric Field Alignment

One viable method of distributing thermally conductive pathways within the insulating plastic is the alignment of thermally conductive nanoparticles (nPs) through the use of an electric field. Graphite, GnPs, and carbon nanotubes are relevant materials that could be used in this method; they are light and possess a significantly high thermal conductivity. Although electrically aligned materials have been proven to provide better pathways than randomly distributed particles, there are still issues where the material will not reach through the entire layer of insulating polymer and the pathways will be incomplete. Figure 1 compares four scanning electron microscope (SEM) images taken by Shuying et al. of GnP alignment with the application of an AC electric field. Over a short period of time, a defined alignment is achieved. Thermal conductivity in parallel to the alignment increased approximately 50% compared to randomly distributed GnPs [5]. One major benefit of this application is that noticeable improvement can be observed even at low volume content of GnPs. In this particular study, an almost 50% conductivity improvement (Figure 2) was observed even 1.08 vol% GnPs when compared to unfilled epoxy [5]. Additional to graphene, ceramics such as aluminum nitride (AlN) and boron nitride (BN) have been studied under induced electric field. A study by Myojo et al., has shown an improvement of up to a factor of 30 when compared to unaligned base polymer [6].

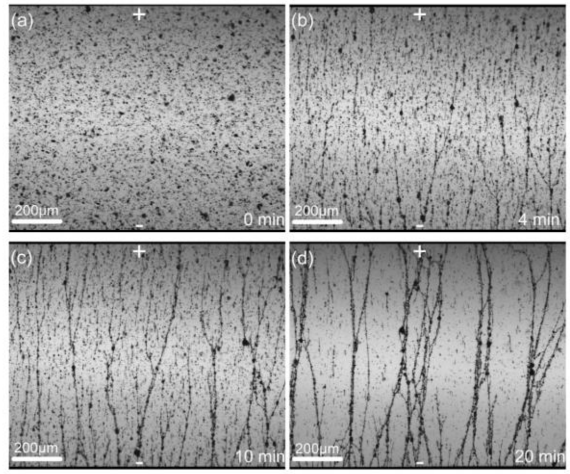


**Figure 1:** GnP alignment with the application of an AC electric field of 25 V/mm where a) is at time, t= 0, b) after 4 min, c) after 10 min and d) after 20 min [5].

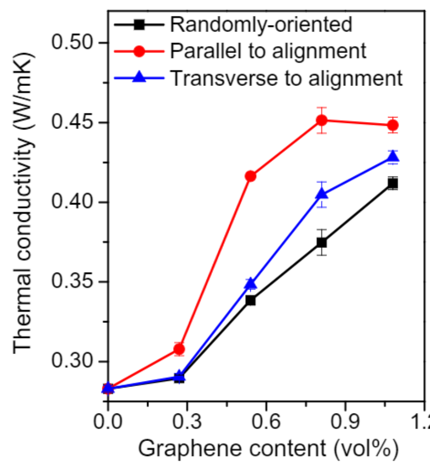


**Figure 2:** Thermal conductivity in various trajectories with increasing graphene content [5].

### 3.4 Acoustic Alignment

Acoustic waves can be deployed to displace randomly dispensed particles. The use of acoustic waves to shift particles draws the inserted material to the points of low pressure, or nodes. [7] There is a dependency on the wave frequencies deployed on the fluid [7]. In multi-nodal systems, nodes are located half a wavelength apart; to create many pathways or nodes in a given length, the wavelength must be much smaller than the panel length in the direction of the wave travel.[7]. Questions arise in whether the vibrations, drawing material closer to nodes, would affect the polymer as well. If polymer is drawn to nodes and away from anti-nodes, the fully formed extractor may not be able to withstand fluid at the anti-node locations and breakdown faster during use.

## 4 COMPLICATIONS AND DEFECTS

Embedding a polymer extractor with a second material is difficult. Damage can occur due to the two different thermal expansion values the materials will possess as well as due to strains on the crystalline structure of the polymer. The volume a material changes with its average temperature, and a differing thermal expansion value would mean that the rate at which this volume changes is different for each material. The heat extractor system can experience temperatures varying as much as 70°C, so both the insulating polymer and the thermally conductive filling will experience significant expansions and contractions. If the polymer expands in the heat more than the inserted material, then the plastic may be damaged, and fluid may leak. The polymer and the thermally conductive insert must be able to operate in this range and handle the volume changes due to temperature fluctuations.

On a molecular level, defects within the polycrystalline structure are expected. The addition of nano-scale fillers causes a strain in the polymer matrix, which has been shown to produce cracks in the lattice structure that may propagate to a larger scale (see Figure 3). In one study, cracks formed by electric field alignment were found to be formed mainly due to the disproportionate Young's modulus and Poisson's ratio between filler material and the polymer [5].

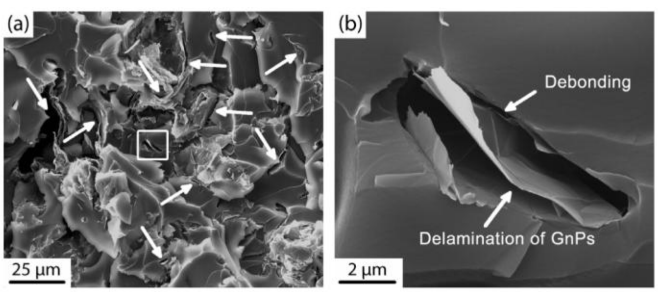


**Figure 3:** SEM images of defects on the surface of a GnP-polymer nanocomposite where the arrows in a) show microcracks around GnP and b) is a close up showing debonding and delamination [5].

## 5 CONCLUSION

This work explored various methods of nanoparticle alignment to effectively enhance thermal conductivity for PV heat extractors. Further characterization is needed to select the most suitable methods of fabrication. Through precise imaging techniques such as scanning electron microscopy, the continuity of carbon-based nanoparticles within the polymer can be determined on a molecular level. Heat conductivity and strength testing must also be conducted with unfilled polymer as the control variable. Highly accelerated life testing (HALT) must be done to determine the effects of the implanted nanoparticles being repeatedly heated and cooled as they are currently unknown. Moreover, defects caused by fabrication methods may present unforeseen challenges that could lead to fluid leakage.

Although these fabrication methods are promising, it is yet to be proven to be manufacturable at large production scales. For now, nano surface treatments (such as ones being developed by Interphase Materials, Inc.) could be applied externally to reduce material stress as well as enhance thermal conductivity. A combination of these state-of-the-art solutions will improve the conversion efficiency of the heat extractor system, and lead to tremendous positive environmental impact.

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