Research Paper

Enhancing Dry Cooling in Power Plants through High-Conductivity Thermal Ground Planes

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Abstract:
As global electricity demand increases, the majority of power is produced by thermoelectric plants using fossil and nuclear fuels, despite the rising role of renewables like solar and wind. These plants typically dissipate about 60% of generated heat, often through water cooling, which poses sustainability issues due to significant water usage. With ongoing water shortages, there's a shift towards alternative dry cooling methods that use air, but these methods face efficiency challenges due to air's lower thermal properties. This study introduces high thermal conductivity thermal ground planes (TGPs) as fins in dry cooling systems to overcome these challenges. TGPs, encapsulating a phase-change material, exhibit thermal conductivities tens to hundreds of times higher than metals, leading to rapid heat dissipation. My experimental results show TGPs achieving effective thermal conductivities up to 30,000 W/mK, significantly outperforming traditional aluminum fins. Simulating TGPs in a 600 MW power plant's dry cooling system indicated a 2.5°C reduction in turbine discharge temperature, a 0.8% efficiency increase, 1% lower coal consumption, and fuel cost savings of approximately $500,000 annually. This approach not only reduces water dependency, but also enhances dry cooling efficiency and operational costs in power plants.

1. BACKGROUND AND INTRODUCTION

In the context of rapid population growth and the enhanced quality of life, global electricity demand has soared from less than 12,000 terawatt-hours (TWh) in 1990 to 29,000 TWh in 2022, as shown in Figure 1 [1].

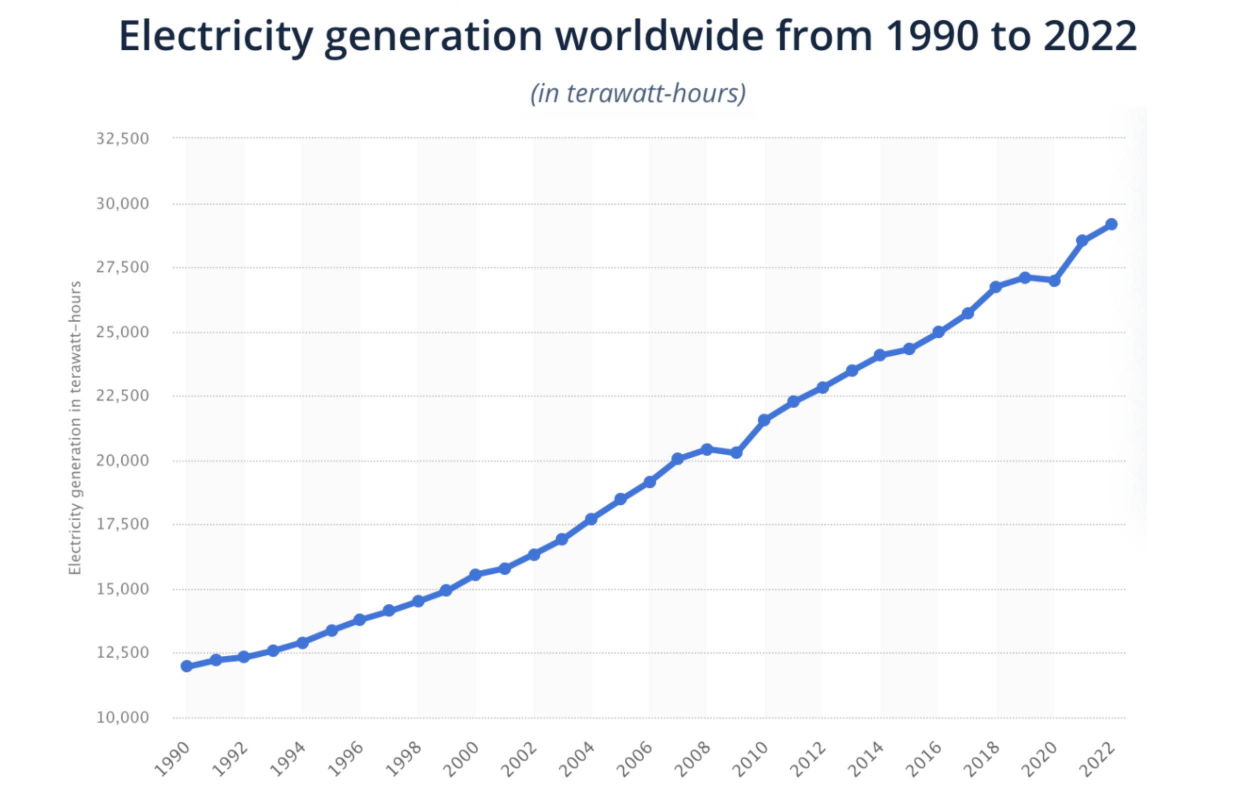

Figure 1: Total electricity generation worldwide from 1990 to 2022 based on various sources such as renewables, nuclear power, fossil fuels. [1]

While renewable energy, such as wind power and solar photovoltaics, has increased in percentage in recent years, over 90% of electricity used worldwide today is still generated by thermoelectric power plants, including traditional power plants burning fossil fuels like coal, oil, natural gas, and nuclear power plants [2]. When fossil fuels and radioactive nuclear fuels are burned to generate electricity, the process involves steam or gas turbines and electric generators that convert energy into electricity. However, approximately 60% of the heat produced from these fuels is not used for electricity generation and must be released through the use of condensers into the environment, including air and water bodies. When heat is directly dissipated to air, the process is known as dry cooling. When dissipated to water, including lakes and rivers, the process is called wet cooling [3].

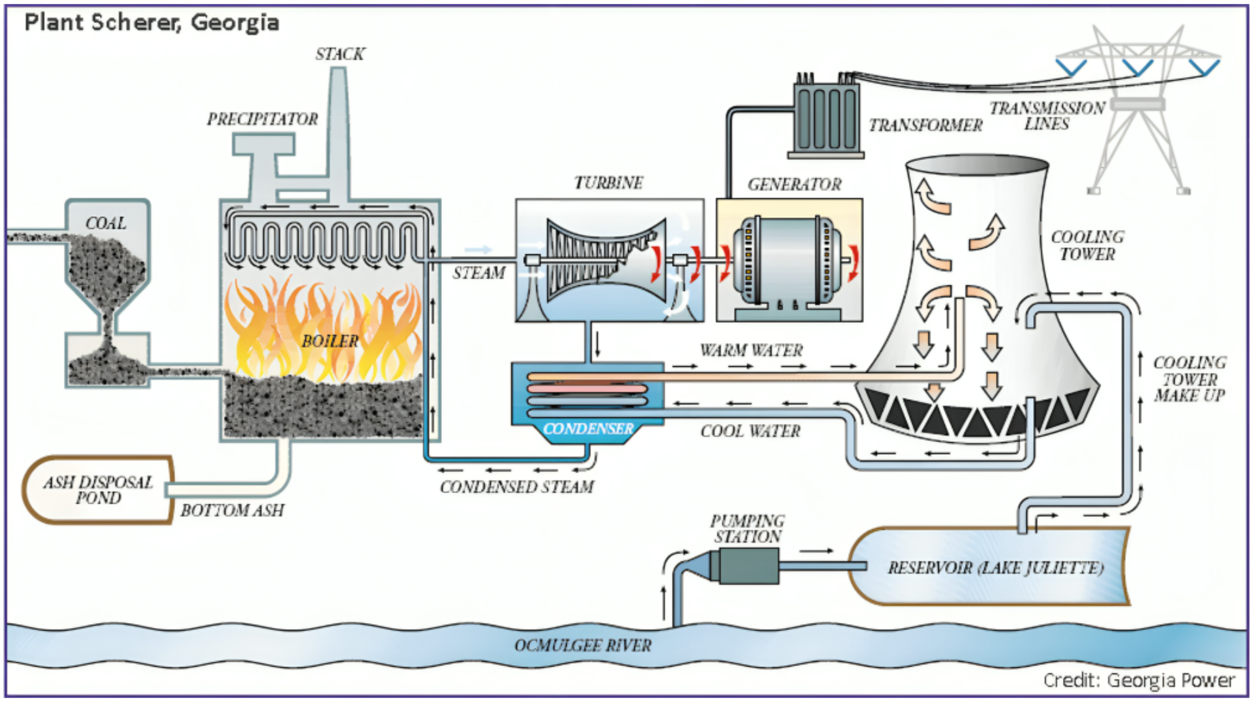

Figure 2: Schematics of a coal-fired power plant: coal is burned to boil water to drive turbines for electricity generation. 60% of the heat needs to be dissipated to the environment. [4]

Wet cooling systems are largely water-intensive. Power plants with water cooling systems face heightened constraints, accounting for 41 percent of total water withdrawals across the United States in 2015, with more than 3% lost through evaporation [5]. The primary cause of high water usage stems from the need to dissipate more heat than the electricity generated, with a ratio of 60% dissipated to 40% converted to electricity for power plants. By lowering the turbine discharge temperature, there is potential to generate more electricity and produce less waste heat [2]. Estimates by the World Bank show that the world will face a 40% shortfall between forecast demand and available water supply by 2030 [6]. Water is an important source for our everyday use, from agriculture and industry to electricity generation. Without advancements in cooling technology, both water conservation efforts and electricity generation capacity could be severely impacted. This scenario necessitates the development and implementation of more sustainable cooling technologies with lower or even no water dependence.

Wet Cooling Systems

Wet cooling systems work by circulating large amounts of water to absorb excess heat from turbine discharge during power generation. Once-through systems, as illustrated in Figure 3, draw water from nearby sources like rivers or lakes, pass it through condensers to absorb heat, and then discharge the warmed water back into the source. Despite their initial popularity due to simplicity, high cooling efficiency, and low cost, they have become less favored due to their impact on local ecosystems, challenges in finding suitable water sources, and contribution to thermal pollution.

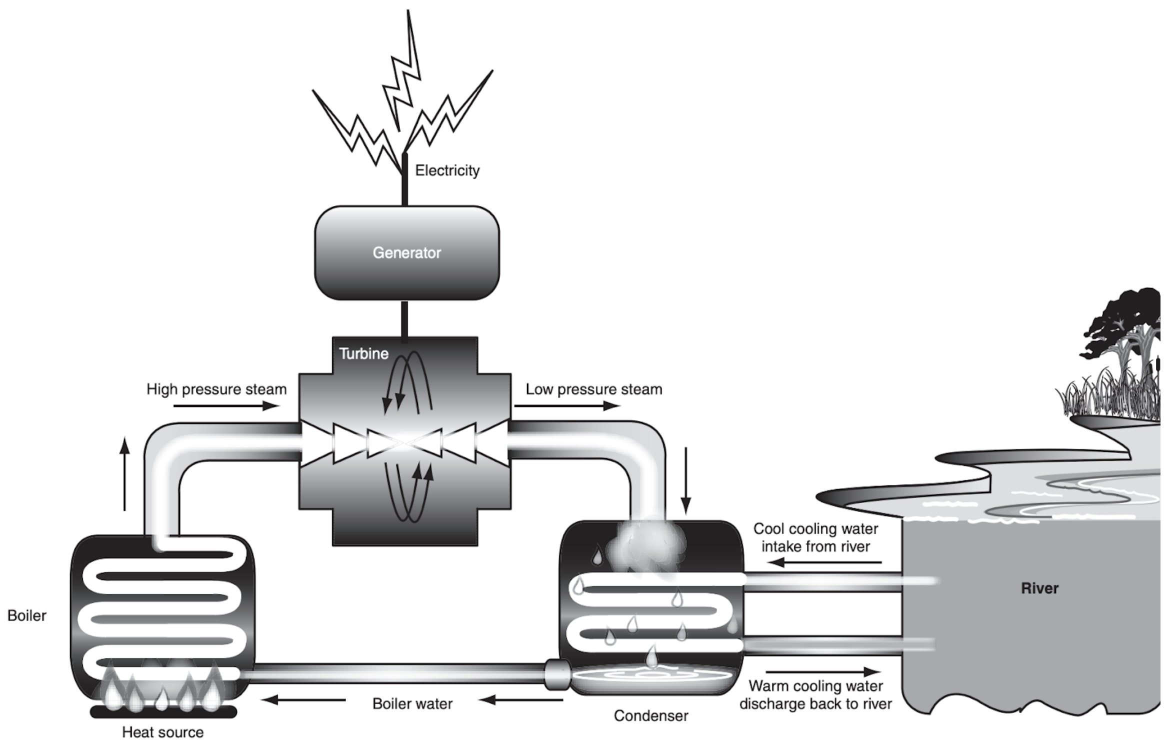

Figure 3: Diagram of once-through cooling system. [7]

In contrast, wet-recirculating or closed-loop systems, as shown in Figure 4, provide a more efficient and sustainable cooling approach. These systems use cooling towers to facilitate the heat exchange process with ambient air. Water is exposed to the air in the towers, where some of it evaporates. The remaining water is then returned to the power plant's condenser for reuse.

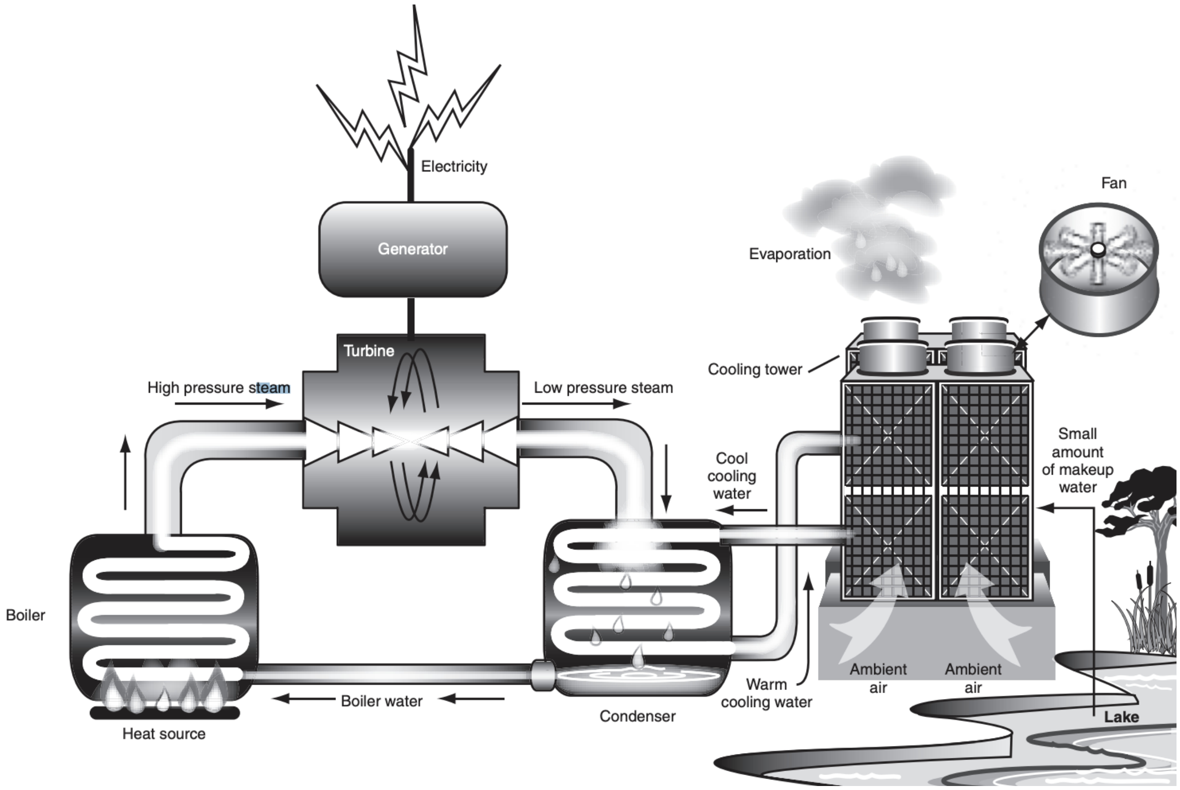

Figure 4: Diagram of circulating wet cooling system. [7]

While wet-recirculating systems have lower water withdrawals compared to once-through systems, they tend to have higher water consumption due to evaporation. This approach is more prominent in the western United States, where water resources may be scarcer, highlighting the adaptability of cooling systems to regional conditions [3]. While these conventional cooling systems have been effective in maintaining operational conditions, it is important to further study alternative cooling technologies that are less dependent on water and are more environmentally friendly.

Dry Cooling Systems

Dry cooling technologies are a potential alternative solution to combat water scarcity and environmental protection. Rather than using water, these systems rely on atmospheric air for dissipating heat from power plants. Dry cooling technologies can reduce total power plant water consumption by over 90%. The key to such a cooling system is the air-cooled heat exchangers, which efficiently conduct the waste heat discharged from the turbine away into the surrounding air (Figure 5).

Figure 5: Image of dry cooling system. [8]

In air-cooled systems, there are two main types of technologies involving direct and indirect dry cooling. Direct dry cooling uses high-flow forced air to cool the steam by passing it through a system of finned tubes. The heat is then directly transferred to the ambient air. On the other hand, indirect dry cooling uses a condenser cooling circuit where water is enclosed. It is cooled by a flow of air past finned tubes in a cooling tower, and heat is transferred to the air [3].

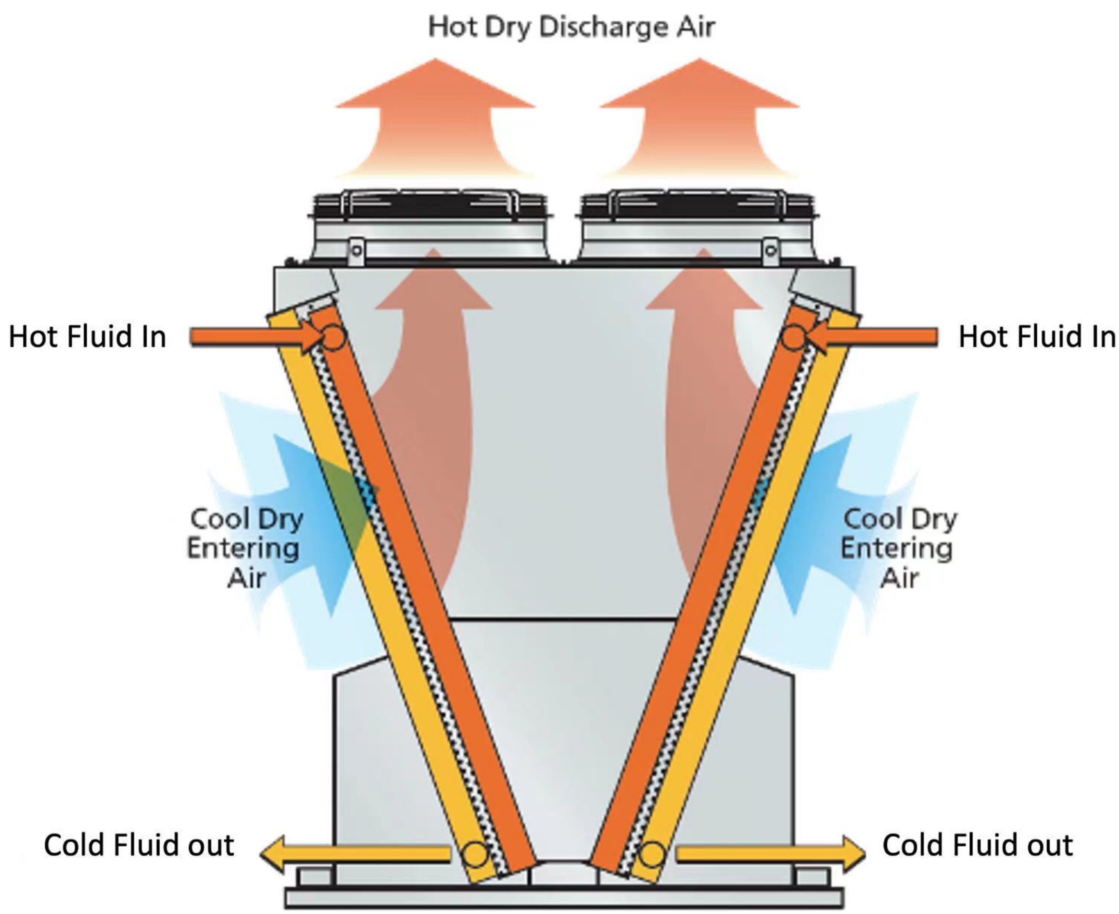

Figure 6: Schematic diagram of dry cooling system with air cooled condenser. [9]

Although dry cooling systems do not use as much water, this technology still faces some limitations, because air is not as effective in heat transfer as water due to its low thermal conductivity and low heat capacity. To increase the heat dissipation efficiency of condensers, aluminum fins, functioning like an extended surface similar to a car radiator, are often used. One of the primary concerns with dry cooling systems is their energy efficiency. They generally consume more energy to cool compared to wet cooling systems, leading to higher operational costs and fuel requirements. Additionally, during hot weather, the rise in air temperature can also reduce the cooling efficiency of the system, impacting power plant operation. Typically, the efficiency of fins is linked to the thermal conductivity of the material used to make them. Aluminum, with a thermal conductivity of 237 W/mK, is lower than copper (398 W/mK), but much lighter and thus is often used as fins for condensers. In a typical design of a dry cooling condenser of a power plant, the aluminum fin efficiency is only 70 to 85%, leaving room for efficiency improvement.

The goal of this project is to use a material with ultra-high thermal conductivity to make fins for condensers, enhancing the efficiency of the condensers and, consequently, the efficiency of thermoelectric power generation. By improving fin efficiency through a better conductive material, more heat can be exchanged to the ambient air which helps in condensing the steam in the power-generation thermodynamic cycle.

Thermal Ground Planes (TGPs)

Thermal ground planes (TGPs) are a novel technology that can significantly improve heat transfer efficiency. TGP was invented by Professor Y.C. Lee and a group of colleagues in the Department of Mechanical Engineering at the University of Colorado Boulder about 15 years ago. Professor Y.C. Lee founded Kelvin Thermal Technologies LLC in 2013 to commercialize TGPs for cooling of smartphone and laptop computers. TGPs can now be made with copper enclosures and polymer enclosures [21]. Figure 7 illustrates an image of a polymer-cased TGP with dimensions of 256 mm x 105.6 mm x 0.5 mm.

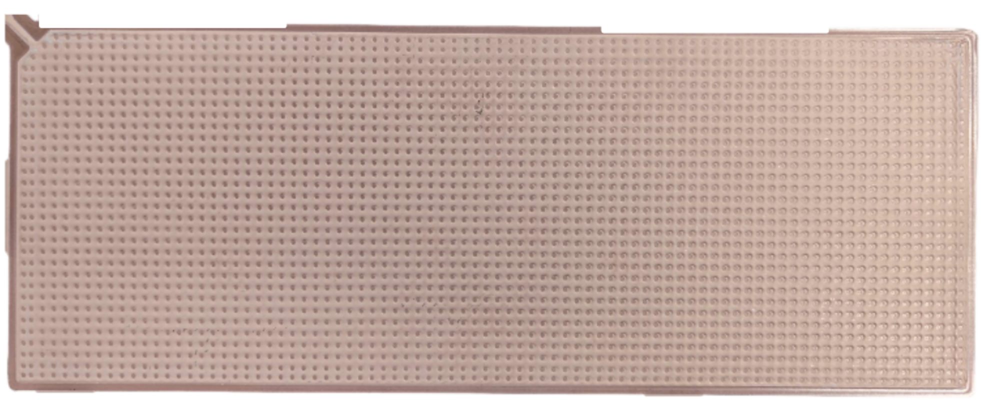

Figure 7: Image of 256 mm x 105.6 mm x 0.5 mm TGP made by Professor Y.C. Lee from Kelvin Thermal Technologies and University of Colorado Boulder.

TGPs are vacuum-sealed thin enclosures filled with a working fluid like water. Within the enclosure is a wicking material that absorbs heat and evaporates the fluid (Figure 8). This evaporation of water and transport of vapor spreads heat across the plane, and the vapor condenses back to liquid, returning to the heat source through the capillary force of wick. This cycle of liquid-to-vapor and vapor-to-liquid phase changes enables excellent heat distribution across the entire surface.

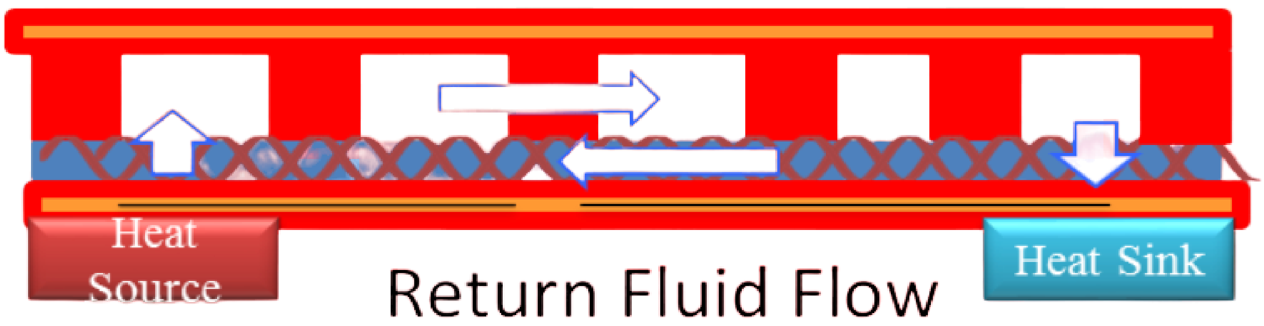

Figure 8: Illustration of the working mechanism of TGPs. It transfers heat from heat sources across the entire plane through two-phase transition and flow:
Evaporation → Vapor Transport → Condensation → Fluid Flow.
Diagram provided by Kelvin Thermal.

A key advantage of TGPs is their ultra-high effective thermal conductivity, which can exceed that of metals like aluminum by one to a few orders of magnitude, reaching several thousands of W/mK. Additionally, TGPs can be made very thin (0.2 mm-0.5 mm) and lightweight. Their combination of exceptional conductivity and low weight makes them well-suited for applications needing efficient heat transfer.

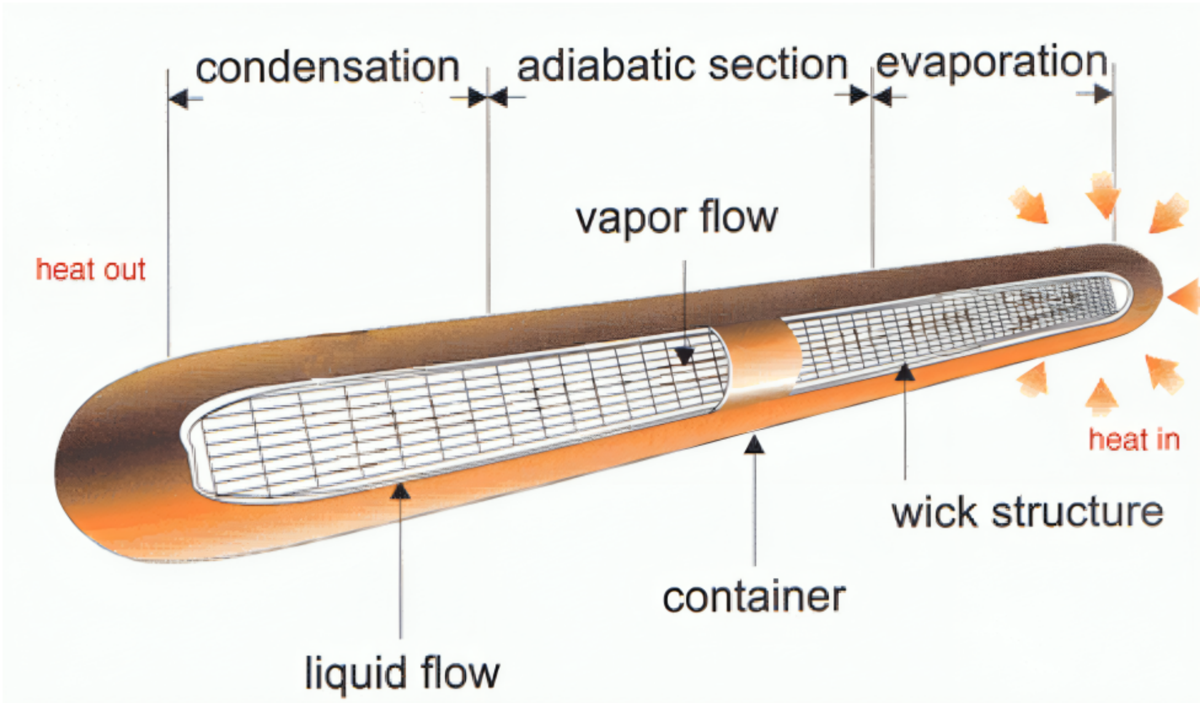

Figure 9: TGP works in a similar principle as a heat pipe, but in a rectangular enclosure. [10]

Using TGPs as fins in the dry cooling condensers of thermoelectric power plants has the potential to significantly improve the efficiency of the condensers by enhancing heat transfer to the air, improving from the current 70-90% fin efficiency of aluminum. In turn, enhanced efficiency of the condensers could boost overall plant efficiency, reduce fuel usage, and help mitigate water scarcity issues facing traditional wet cooling methods. Although TGP fins may advance sustainability in power generation, this application has yet to be thought of, tested, or implemented.

2. METHODS

TGPs have a significantly higher thermal conductivity than aluminum. They are lightweight and thin, making them suitable alternatives to aluminum in conventional dry cooling condensers. By replacing aluminum with TGPs, the efficiency of the condenser can be improved. This configuration leads to a lower discharge temperature of the turbine, allowing for increased efficiency of the power plant and reduced fuel consumption. The objectives of this project are to conduct a hands-on study on the high thermal conductivity of TGPs, and to explore the feasibility and benefits of utilizing TGPs to enhance power plant efficiency and reduce fuel consumption.

Part One: Experimental Comparison on Thermal Performance of TGP and Aluminum

The first part of the study involved a comparative experimental analysis on the heat transfer performance of thin TGP and aluminum plates, which are traditionally used as fins in dry cooling systems. TGPs were provided by Kelvin Thermal Technologies and constructed from flexible printed circuit boards and were compared against aluminum plates of the same dimensions. The dimensions for both material pieces were set at 256 mm x 106.8 mm x 0.5 mm (Figure 10).

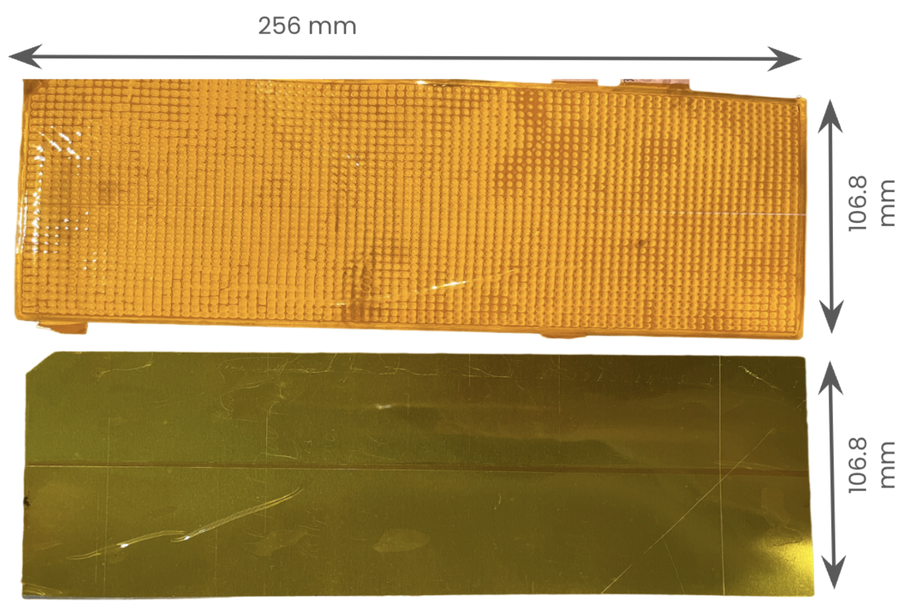

Figure 10: TGP and Aluminum plates in the same dimensions with kapton tape.

In the experimental process, heat was applied to the TGPs using an electric heating element, and the resulting temperature was measured with an infrared camera, averaging from 5 corner points and 5 center points per plate. This procedure was repeated for 5 varying levels of input power to thoroughly test the performance of the TGPs compared to aluminum. Due to material and safety constraints, the heater was limited only to temperatures under 85°C, resulting in the test of power inputs ranging from 1.36 W to 18.58 W.

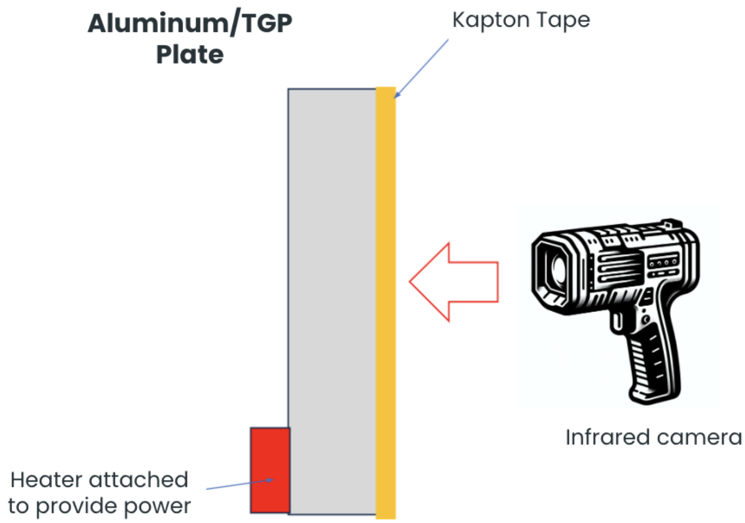

Figure 11: Diagram of experimental process involving heating of an aluminum/TGP plate with an attached electric heater and the measurement of the temperature change using an infrared camera.

Statistical analysis, including *t*-Tests, were conducted between the temperature change values of the aluminum and TGP on a sample size of 20 temperature points each to determine the statistical significance of the differences in performance at $p < 0.05$.

When heat is applied to the plates, it conducts along both the aluminum and TGP plates to the air, following the same principle observed in condenser fins. To determine the thermal conductivity of the TGP, the initial step involves determining the natural convective heat transfer coefficient. Theoretical calculations were completed to evaluate the convective heat transfer coefficient on aluminum, which was then used to determine the effective thermal conductivity of the TGPs because all other measurement conditions remained the same. MIT's procedures on heat transfer from a fin, as described in Equation 1, served as the framework for these calculations, where: Q is the heat transfer rate, k is the thermal conductivity, h is the convective heat transfer coefficient, A is the cross-sectional area, P is the perimeter, T_0 is the base temperature, T_∞ is ambient temperature, m is the shape factor and m = hp/KA, and L is the length.

$$\frac{Q}{\sqrt{kAhP}\,(T0\text{-}T\infty)} = \tanh(mL)$$

Equation 1: Calculation of heat transfer from a fin [11]

Part Two: Scale-Up Simulation for Dry Cooling System

Following the experimental comparison, the study progressed to a scale-up simulation that reflects the practical application in a power plant's cooling system. This simulation is based on the experimental results and is designed to emulate a larger and more complex system, resembling the cooling process of a power plant.

Calculations to determine the heat removal using TGPs as fins were conducted, again using Eq. 1, for different convective heat transfer coefficients. Then, in collaboration with a thermal engineer at the company EVAPCO, the world-leading dry cooling technology provider for power plants, a simulation was made in an effort to reflect a real-world power generation application.

A simulation was conducted using a condenser design software to assess the cooling performance of a 600 MW power plant's dry cooling condenser system. Specifically, the study investigated the effects of replacing the 1.2 million m^2 fins with high thermal conductivity TGPs. The calculations aimed to evaluate the turbine discharge temperature with the new condenser configuration. The results from these calculations are expected to demonstrate the potential of TGPs in significantly improving the efficiency of dry cooling systems in power plants, contributing to sustainable energy production and addressing the challenges of water scarcity and environmental sustainability.

3. RESULTS

Part One: Experimental Comparison

Figure 12 shows a scatter plot with linear regression line and error bars for average temperature vs. power of TGP and Aluminum plates. The slope of the temperature rise with increasing power for each material provides insight into their heat dissipation efficiencies. The TGP has a slope of

1.94, while aluminum has a higher slope of 3.34. The difference in slope indicates that aluminum heats up more quickly than TGP at the same power input level, indicating a lower heat spreading efficiency. As illustrated in Figure 12, 95% confidence intervals suggest with 95% certainty that the true mean is within the range.

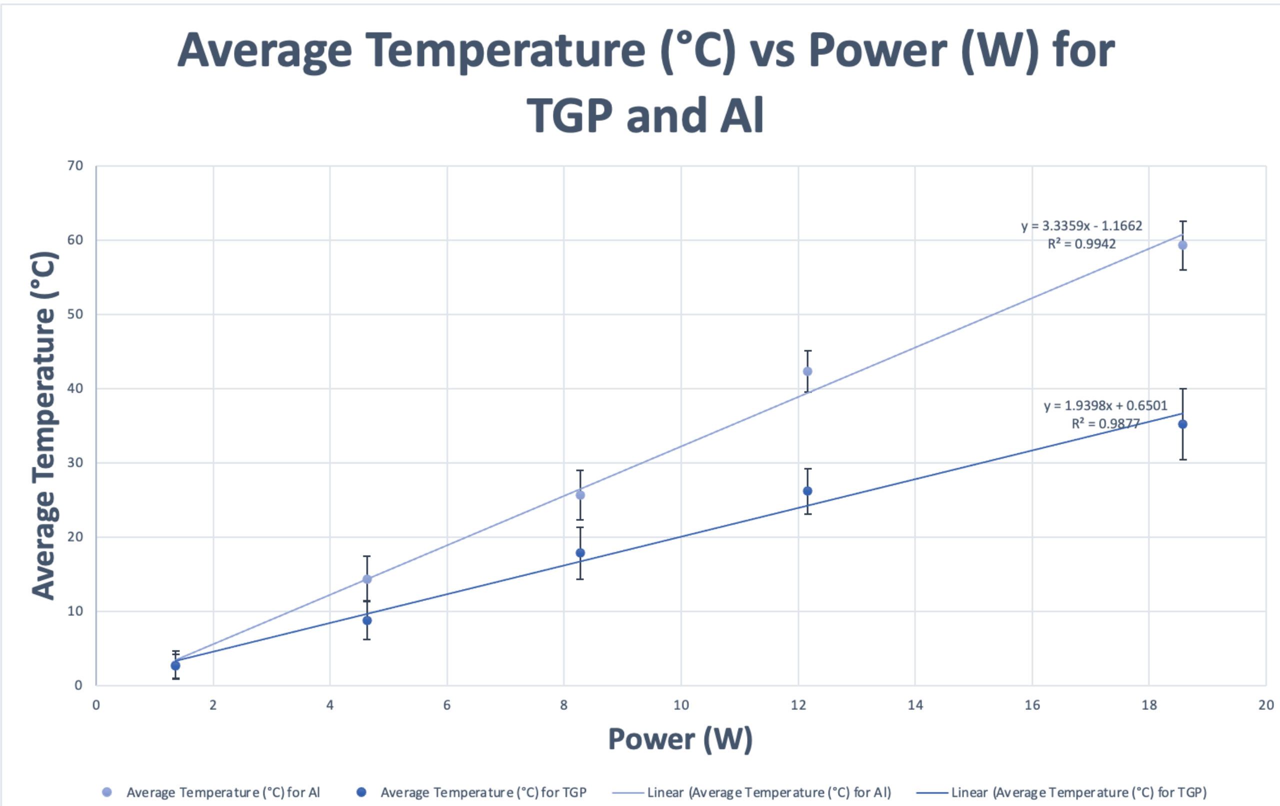

Figure 12: Scatter plot with linear regression line and error bars for average temperature vs. power of TGP and Al plates.

Statistical comparison of TGP and Aluminum with varying power inputs:

Means for temperature with a power input of 1.36 W **are *NOT*** significantly different ($p < 0.05$) as revealed by a Student's t-Test: Al vs TGP ($t = 0.18$) at an α of 0.05 and t_{crit} of 2.02.

Means for temperature with a power input of 4.63 W ***are*** significantly different ($p < 0.05$) as revealed by a Student's t-Test: Al vs TGP ($t = 6.23$) at an α of 0.05 and t_{crit} of 2.02.

Means for temperature with a power input of 8.27 W ***are*** significantly different ($p < 0.05$) as revealed by a Student's t-Test: Al vs TGP ($t = 7.24$) at an α of 0.05 and t_{crit} of 2.02.

Means for temperature with a power input of 12.17 W ***are*** significantly different ($p < 0.05$) as revealed by a Student's t-Test: Al vs TGP ($t = 17.42$) at an α of 0.05 and t_{crit} of 2.02.
Means for temperature with a power input of 18.58 W ***are*** significantly different ($p < 0.05$) as revealed by a Student's t-Test: Al vs TGP ($t = 18.55$) at an α of 0.05 and t_crit of 2.02.

Based on the experimental values of power and temperature, the convective heat transfer coefficient for aluminum was calculated to be h = 4.87 using Equation 1 in a natural air convection environment. Using this coefficient as an input value, the effective thermal conductivity of TGP was determined, with values ranging from 19,000 W/mK to 30,000 W/mK for varying power inputs. Notice that the effective thermal conductivity increases with higher power input, rather than the constant value observed in aluminum at 237 W/mK. This deviation occurs because as long as the material does not burn out, higher power input results in a more dynamic phase-change of the liquid inside, leading to enhanced thermal conductivity.

Table 1: Effective thermal conductivity values for TGP for varying power inputs.

Power Inputs (W)	Effective Thermal Conductivity (W/mK) of TGP
1.36	25,600
4.63	26,500
5.39	27,400
12.17	28,400
18.58	31,800

The effective thermal conductivity values for TGP are substantially higher than the known thermal conductivity of aluminum (237 W/mK). The high thermal conductivity of TGP indicates its potential for highly efficient heat transfer, making it an excellent candidate for improving cooling technologies in power plants.

Part Two: Scale-Up Simulation for Dry Cooling System

Extended surfaces, such as aluminum fins, are known for their ability to enhance the heat transfer of heat exchangers such as dry cooling condensers. This principle is similar to the mechanisms observed in car radiators and air conditioning condensers. However, the convective heat transfer coefficient (h) was varied in different systems due to their different operational scenarios, ranging from natural convection of 5 W/m^2K to several hundred due to forced convection. Figure 13 shows the heat removal capability of a TGP fin and an aluminum fin assuming different convective heat transfer coefficients. Specifically, for power plants, dry cooling condensers are designed to be subjected to a wind velocity of 3 m/s, and the convective heat transfer coefficient was calculated to be 30 W/m^2K. From Table 2, at h = 20 W/m^2K, TGP dissipates 121 W, much higher than 71 W of aluminum.

Table 2: Heat Removal Capability of TGP fin and aluminum fin assuming different convective heat transfer coefficients.

Convective heat transfer coefficient value (W/m^2K)	TGP (k = 30,000 W/mK)	Aluminum (k = 237 W/mK)
h = 4.9	30 W	17 W
h = 30	121 W	71 W
h = 100	430 W	265 W

By substituting the aluminum fins with high thermal conductivity TGPs in a condenser for a 600 MW power plant, which uses 1.2 million square meters of fins, the condenser's efficiency was significantly improved.

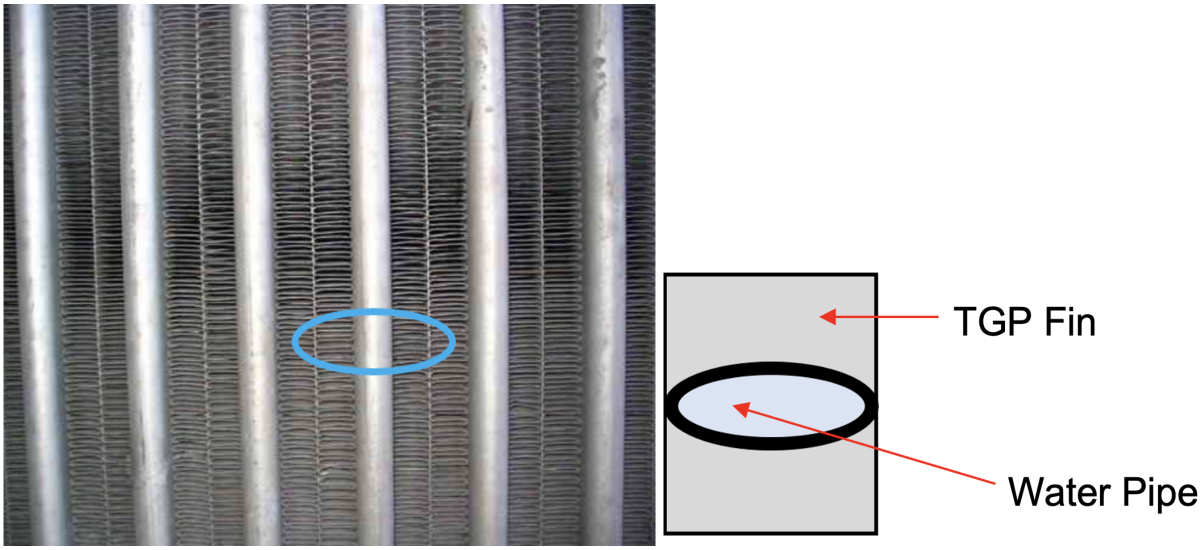

Figure 13: Calculation was performed on a dry cooling condenser of a 600 MW power plant. The aluminum fins are replaced by TGPs. The condenser uses 1.2 million m^2 of fins.

This improvement was demonstrated by more effective cooling of the water discharged from the turbine, where the temperature was reduced from 47.83°C to 45.33°C. This temperature reduction of 2.5°C translates to a notable 0.8% increase in the overall efficiency of a standard 600 MW power plant. Furthermore, in terms of fuel consumption, the use of TGPs resulted in a saving of 3 grams of coal per 1 kWh of electricity generated, from the original consumption of 315 grams. When these savings are scaled for a 600 MW power plant, the reduction in coal consumption could result in cost savings exceeding half a million US dollars.

4. DISCUSSION

Enhanced thermoelectric power generation efficiency can lead to reduced fuel consumption, reduced costs and a smaller environmental footprint. The experimental results clearly showed that TGPs have exceptionally high thermal conductivity, 19,000-30,000 W/mK depending on the heating power, significantly exceeding aluminum used in traditional fins, allowing the dry cooling system to be more energy-efficient. At higher heat loads, TGPs maintained lower temperatures, indicating superior heat transfer capabilities. This efficiency gain could lead to substantial energy savings. The scale-up simulation then confirmed that implementing TGP fins in a full-size plant condenser could improve efficiency by 0.8% and decrease coal consumption by nearly 1%. In economic terms, although TGP systems might have higher initial costs, the reduction in energy consumption can offset these expenses over time. The savings in electricity costs not only make TGP an economically viable option but also contribute to environmental sustainability by reducing the carbon footprint associated with energy use. Other studies use different methods to address water scarcity and more efficient thermoelectric power generation, such as hybrid wet-dry cooling systems or wind-break methods; however, this study leverages a novel heat spreader in replacement of a traditionally used material to improve efficiency. In summary, the transition to more efficient cooling technologies like TGP is driven by the need to address water scarcity, improve energy efficiency, and reduce operational costs. The potential environmental and economic benefits of TGP underscore its relevance in today's increasingly resource-conscious world. In the future, the goal is to implement TGPs into practical applications beyond simulation and conducting experimental work integrating TGPs into a large-scale dry cooling condenser system. The next step is designing a small-scale condenser, possibly with a 1 kW capacity compared to conventional 60 MW systems, utilizing high conductivity TGP fins. This scaled-down system could demonstrate the real-world efficiency improvements possible with TGPs integrated into power plant dry cooling technology. By progressing to physical testing and implementation, the aim is to move this application forward from theoretical calculations and simulations to having a practical, measurable impact on advancing sustainable power generation systems.

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