

Thermal Analysis of Composite Materials

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Abstract- Composite materials have emerged as critical components in the design and manufacturing of aerospace and automotive structures due to their superior mechanical strength, lightweight nature, and customizable thermal properties. This paper presents a secondary study of the thermal behavior of advanced composite materials, focusing on key parameters such as thermal conductivity, coefficient of thermal expansion, thermal degradation resistance, and insulation capabilities. Through a comprehensive review of peer-reviewed literature and technical reports published between 2015 and 2025, this study compares the performance of carbon fiber-reinforced polymers (CFRPs), glass fiber composites (GFRPs), and aramid fiber composites in thermally demanding applications. The analysis highlights how these materials are used in aircraft fuselages, engine components, electric vehicle battery enclosures, and high-performance braking systems. Innovation trends such as hybrid fiber systems, nanocomposite integration, and AI-based simulation tools are also discussed. The findings underscore the importance of selecting composites based on specific thermal requirements and application contexts. Additionally, the paper identifies challenges related to standardization, testing, and cost that continue to affect material adoption. This secondary analysis serves as a foundation for future research and development in the thermal optimization of composites for high-performance engineering sectors.

Keywords: Composite materials, thermal analysis, carbon fiber, aerospace engineering, automotive composites, thermal conductivity, nanocomposites, secondary research, thermal expansion, heat resistance.

I. INTRODUCTION

Composites are man-made materials that are made up of two or more layers with very different chemical or physical properties.

When you mix them, you get something that is different from the parts that made it up.

Fibres made of carbon, glass, or aramid are often used to strengthen alloys that are made of polymers, metals, or ceramics. Composites are used a lot in many fields because strong, lightweight, and high-performance materials are needed more and more. This is especially true in the car and aerospace industries, where thermal stability and structural efficiency are very important.

Composites are important in aeroplanes because they lower the weight of the structure without reducing its strength, which saves fuel and makes the planes more capable of carrying loads. In the same way, composites improve the performance, crash in the car industry [1]. But the temperature behaviour of composite materials is one of the most important and complicated design factors to think about.

Thermal conductivity, thermal expansion rate, and thermal deterioration all have an effect on how well a material insulates, how long it lasts, and how well it works in high-temperature situations. Composites have qualities that aren't uniform and aren't all the same, which makes it hard to understand how they react to heat, even though this information is very important [2]. This is different from metals and ceramics in that the thermal reactions of composite materials depend on how the fibres are arranged, the volume percentage, and the interfacial bonding. Because they are so complicated, we need to study their temperature properties and how well they work in real life right away. The main goal of this study is to look into the thermal properties of advanced composite materials using secondary research. Some of the goals are to look at new studies on important thermal factors, compare different composites, and find out how they work in real-life automotive and aerospace systems. The main goals of this work are to bring together information from different sources in order to show how to choose materials based on their thermal performance and find possible study

gaps that could lead to new ideas in the future. All the information used in this study came from outside sources, like scholarly papers, government reports, and case studies from different fields that came out in the last ten years. This study looks at a lot of different sources to give an opinion based on facts about the present and future of thermal analysis in composite material uses.

II. METHODOLOGY

A descriptive and analytical review method based on secondary research is used in this work, with a focus on thermal study of composite materials. This study used a lot of good sources, such as journal pieces, technical conference papers, white papers, and studies from well-known aerospace and automotive companies. Only research papers released between 2015 and 2025 that talked about the thermal behaviour of composite materials (like how they conduct heat, expand, break down, and stay stable) were looked at when the sources were chosen. The main focus was on materials that are often used in high-performance applications, like carbon fiber-reinforced plastics (CFRPs), glass fibre composites, and new hybrid and nano-enhanced composites. We used comparative methods to look at the data from these sources and find trends, similarities, and differences in how well different types of materials and uses handled heat. The results were summed up, and trend charts and table comparisons were used to back up the conclusion. We can show the latest research in composite thermal properties along with proof to back it up in this way. We can also show how these materials have been used in new ways in aerospace and automotive engineering.

III. THERMAL PROPERTIES OF COMPOSITE MATERIALS

Composite materials, owing to their heterogeneous structure, exhibit complex thermal behaviors that significantly influence their performance in engineering applications. Their thermal properties—such as thermal conductivity, coefficient of thermal expansion, thermal degradation resistance, and stability—are highly dependent on the type of

reinforcement fiber, the matrix material, the fiber orientation, and the interface quality. This section provides a secondary analysis of these properties based on findings from the literature.

Thermal Conductivity

Thermal Properties of Composite Materials

Composite materials exhibit complex thermal behaviors due to their heterogeneous structure, which significantly influences their performance in engineering applications [3].

These thermal properties—encompassing thermal conductivity, coefficient of thermal expansion (CTE), thermal degradation resistance, and overall thermal stability—are governed by several interacting factors, including the type of reinforcement fiber, matrix composition, fiber orientation, and the interfacial bond quality between constituents. As engineering systems are increasingly subjected to high-temperature environments and rapid thermal cycling, understanding the thermal behavior of composites becomes crucial in predicting their long-term durability and functional efficiency across diverse applications.

Thermal conductivity

One of the most critical parameters influencing thermal performance is thermal conductivity, which dictates the material's ability to transfer heat. The thermal conductivity of composite materials depends on the intrinsic thermal conductivities of both the fiber and the matrix, the volume fraction of the reinforcement, the geometric orientation of the fibers, and the quality of the fiber-matrix interface. Carbon fiber-reinforced polymers (CFRPs), for instance, are known for their high thermal conductivity along the fiber axis due to the excellent conductive properties of carbon fibers [4]. This directionality in thermal behavior—known as anisotropic conductivity—is particularly pronounced in unidirectional CFRPs, where heat is conducted efficiently along the aligned fibers but poorly in the transverse direction.

On the other hand, composites strengthened with glass or aramid fibres have much lower thermal conductivity values, usually staying below 1.5 W/m-K. This makes them better for uses that need to insulate

against heat. Because they don't let heat flow easily, these materials are often used in the transportation and aircraft industries as insulation panels, thermal shields, and cabin linings. Researchers say that the heat conductivity of CFRPs can be 20–30 W/m·K in the fibre direction, which is very different from glass fibres. In addition, composites that are woven or randomly orientated tend to have more uniform thermal behaviour, but they also have lower peak conductivity because the heat paths are not lined up in a straight line. Because of this, engineers can make composite structures fit specific thermal management needs, like making sure that heat escapes quickly from electronic cases or keeping heat in during cold climates.

Coefficient of thermal expansion (CTE) is another important thermal feature of composites. It tells us how a material changes shape when temperature changes. Because they aren't uniform, composite materials often have different rates of expansion along different directions. In CFRPs, this is especially clear because the longitudinal CTE (parallel with the fibre axis) can be very low or even negative. This is because carbon fibres are very stiff and their thermal dimensional stability is very good. The transverse CTE of these materials, on the other hand, is usually a lot higher, which can cause problems like mismatched thermal strains or bending after being exposed to heat for a long time. This unevenness calls for accurate modelling and planning in engineering, especially in situations where there are big temperature differences or lots of heating and cooling cycles, like on aeroplane fuselage skins, turbine blade coatings, or electronic circuit boards. Low CTE values are also found in aramid fibres, which makes composites more stable in places where small changes in size are needed. In comparison, glass fibre composites have CTEs that are higher and more uniform. This lowers anisotropy and may cause them to expand more noticeably when they are heated. Studies [5] show that unidirectional CFRPs can have longitudinal CTE values between -0.5 and $+1$ ppm/°C, while the crosswise values can be more than $+30$ ppm/°C. This shows how important it is to understand CTE. This difference makes it even more important to think about temperature directionality when designing structures, especially when

combining composites with metals or ceramics that expand and contract at different rates.

When looking at how well composites will work in high-temperature settings over time, thermal degradation and heat resistance are also very important. When polymers are exposed to high temperatures for long periods of time, they break down chemically and physically. This is called thermal deterioration. Because they can handle high temperatures so well, thermosetting plastics like epoxies and phenolic resins are often used in high-temperature situations. They can often keep their shape up to 250–300°C. However, thermoplastic matrices break down at lower temperatures. Adding high-performance support fibres and nanofillers can improve their performance, though. When it comes to heat protection, carbon fibres are especially helpful because their high thermal conductivity helps get rid of localised heat, which slows down the breakdown of the matrix. Incorporating nanofillers like graphene flakes or carbon nanotubes has also shown promise in making things more stable at high temperatures. In the matrix, these nanostructures can connect to make conductive networks that improve both heat conductivity and the point at which the material starts to break down. Aerospace studies [6] have shown that CFRP composites can keep more than 80% of their original mechanical strength even after being exposed to 200°C for a long time. This makes them perfect for parts that are heated and cooled over and over again, like engine cases, thermal shields, and structural panels. The thermal degradation profiles of polymer composites are also getting better thanks to the creation of fire-resistant resin systems and heat-resistant coatings. This means that they can be used in settings with higher temperatures.

While thermal stability and degradation are linked, thermal stability specifically refers to a material's ability to keep its mechanical and physical properties when it is heated over and over again. This is especially important in fields like aircraft, automotive, and energy where materials are heated and cooled many times over long periods of time. Because they don't conduct heat well and don't get worn down easily by heat, composite materials strengthened with glass and aramid fibres usually

have great thermal stability. It is possible for these materials to go through many temperature cycles without losing their shape or mechanical strength [7]. For example, tests in the lab and reports from businesses have shown that aramid-reinforced composites can withstand more than 1000 temperature cycles between -50°C and +180°C with little damage to their structure. This kind of performance is important for parts of satellite systems, high-altitude drones, and electric car thermal insulation panels. Besides being stable over time, a composite material's ability to insulate is also very important in situations where thermal safety is needed.

The R-value, which measures a material's resistance to heat flow, is often used to measure its insulation ability. Glass fibre panels can get R-values between 3.5 and 4.5 m²·K/W in insulation tests like the ones set by ISO 8302. This means they can be used for high-performance insulation tasks. The ability of a composite to be both thermally stable and good at insulating opens the door to multifunctional materials that can manage heat and keep structures strong. This means that different insulating parts aren't needed, which makes the system simpler and lighter. The way that thermal conductivity, CTE, degradation resistance, and insulation effectiveness change over time makes composite materials very adaptable for thermal uses. For example, when engineers are making battery enclosures for electric cars, they have to find a balance between the need for good heat transfer (which favours CFRPs) and safety worries about thermal runaway (which may favour aramid or glass fibre composites because they are good at keeping heat in) [8]. In the same way, when designing aircraft parts, there are trade-offs between keeping the dimensions stable over a wide range of temperatures and making sure the parts don't break down from heat. New improvements in hybrid composites, which mix different types of fibres or changes to the binder, make it even easier to tailor these materials to different temperatures. For example, hybrid laminates made of carbon and glass fibres can offer balanced properties by combining the ability of carbon to remove heat and the ability of glass to insulate while still keeping enough mechanical

integrity. Phase change materials (PCMs) that are mixed into the composite matrix are also becoming more popular as a way to quietly control temperature by taking in and releasing heat during phase changes.

In conclusion, the thermal properties of composite materials are multifaceted and highly application-specific. Through careful selection of fibers, matrices, and structural orientation, engineers can design composite systems optimized for a wide range of thermal environments. Whether the goal is to dissipate heat in high-performance electronics, maintain structural precision under extreme temperatures, or insulate against thermal loads, composite materials offer a versatile and efficient solution. Continued research into nano-enhancements, smart materials, and hybrid structures promises to further expand the thermal capabilities of composite materials, solidifying their role as indispensable components in modern engineering design.

Comparative Data from Literature

A synthesis of multiple studies is summarized in Table 1, showing comparative thermal performance across major composite types.

These values highlight the trade-offs in selecting composite materials based on thermal requirements. The literature strongly suggests that no single composite excels in all areas, and material selection should be application-specific based on the thermal environment.

Compo site Type	Thermal Conducti vity (W/m·K)	Longitud inal CTE (ppm/°C)	Degrada tion Temp (°C)	Insulati on Suitabi lity
Carbon Fiber (CFRP)	20–30	–0.5 to +1	250–300	Moder ate
Glass Fiber (GFRP)	0.3–1.5	5–15	200–250	High
Aramid Fiber (AFRP)	0.2–0.6	1–5	180–220	Very High

IV. APPLICATIONS IN AEROSPACE AND AUTOMOTIVE SECTORS

Due to their high strength-to-weight ratio and great thermal properties, composite materials are now essential in many technical fields, especially in the aircraft and automotive industries. In these areas, you need materials that can stand up to mechanical stress and keep working in a wide range of temperatures. Composite materials, especially those reinforced with carbon, glass, or aramid fibres, have been shown to be flexible and effective in these kinds of harsh thermal circumstances.

Applications in the Aerospace Sector

By making parts lighter, composites have changed the way the aerospace business works. Lighter planes use less fuel and can carry more cargo. Carbon fiber-reinforced polymers (CFRPs) are very useful because they are good at resisting heat and letting heat flow in one way. Because they don't change shape when heated, they are great for use as heat shielding panels, engine nacelles, tail booms, and parts of aircraft fuselage. Composite materials are now used on most modern planes made by NASA and other big aircraft companies like Airbus and Boeing. The Boeing 787 Dreamliner is one example [9]. Its body is made of more than half composite materials by weight. This makes the plane much lighter and better able to handle heat and rust. Similarly, the Airbus A350's fuselage and wing sections use CFRPs a lot to deal with the heat that builds up during flight. It can be as cold as -50°C at flying level or as hot as 150°C close to the engine, but these planes can still fly. Composite panels are structurally strong and effectively handle changes in temperature because they contain fire-resistant and thermal-insulating layers. Also, NASA's trips to Mars have used high-performance composites with ceramic or ablative layers to reduce heat during re-entry into the atmosphere. These materials are made to keep their aerodynamic structure by resisting thermal degradation and minimising thermal expansion. The Space Shuttle's nose cone and leading edges of its wings had advanced thermal protection systems (TPS) made of reinforced carbon-carbon (RCC) composites. This showed that composites can be trusted in very hot situations.

Applications in the Automotive Sector

With so many electric cars (EVs) on the road, composites are becoming more and more important in the automotive industry for thermal management systems and structural uses. Composites are used in battery housings, parts that go under the hood, and brake systems because they need to be able to handle sudden changes in temperature, control localised heating, and keep the overall weight of the vehicle low. Carbon fiber-reinforced plastics (CFRPs) and glass fiber-reinforced composites (GFRPs) are being used more and more in the cases of electric vehicle batteries because they are strong, don't let heat escape, and keep heat in. These housings protect the lithium-ion battery cells from damage and keep them from getting too hot when they are being charged and drained quickly. In high-performance models like the Model S Plaid, for example, Tesla's battery design includes a carbon composite housing that helps the battery dissipate heat and protect its structure. These days, engine covers, intake pipes, and radiator supports are made of thermoset and thermoplastic composites. They can stand up to vibrations, engine heat, and fluids that break things down [10]. Their physical stability means that composites don't bend or break mechanically, even when they are put under a lot of heat. Formula 1 cars and other high-performance vehicles use carbon-carbon composites in their brake systems because these materials can handle the very high temperatures (over 1000°C) that come from slowing down without breaking down or losing their ability to stick to surfaces. Composites not only make cars lighter, but they also add thermal and acoustic insulation to the outside panels and structure frames they are used in. This is especially good for hybrid and electric cars because lighter batteries work better and have longer ranges. Hybrid composites that offer both thermal insulation and electromagnetic shielding are being used more and more in current car design. Inside cars, these materials are used for processing units and advanced driver assistance systems (ADAS). These uses show that composite materials are a high-performance, flexible way to deal with heat problems in the aircraft and automotive industries. By changing the matrix, the direction of the fibres, and the materials used, engineers can make parts work better in a range of

temperatures, making them last longer, work better, and be safer.

V. COMPARATIVE ANALYSIS AND DISCUSSION

The secondary literature study says that the thermal behaviour of composite materials depends a lot on the type of fibre used, the matrix composition, the direction of the fibres, and the production methods. Carbon fiber-reinforced polymers (CFRPs) are great materials because they don't expand or contract much when the temperature changes, stay stable at high temperatures, and conduct heat well along the fibre direction. Composites made of carbon fibre are very good at getting rid of heat and keeping their exact shapes even when heated up. Battery housings for electric vehicles and body panels for aeroplanes are two examples of these kinds of uses. Glass fiber-reinforced polymers (GFRPs) and aramid fibre composites are great for protecting against heat, insuring the inside of a car, and using under the hood because they don't let heat pass through them as easily and insulate better [11]. In particular, aramid composites don't expand as much and are very resistant to changes in temperature, but they are usually not as strong mechanically as CFRPs.

When you look at how well different plastics handle heat, it's clear that no one material stands out in every way. For instance, CFRPs are good at conducting heat, but because they are not uniform, they are not very good at handling horizontal heat flow. GFRPs and aramids are better than other materials because they don't conduct heat as well and keep heat in better, especially when they are exposed to cyclic thermal loads. These trade-offs mean that materials have to be chosen based on what they are going to be used for. As a result, mixed composite systems are often used, which combine different fibres or matrices to achieve balanced performance. Brand-new ideas in this field include hybrid materials made of carbon and basalt fibres. Nanocomposite recipes use materials like boron nitride, carbon nanotubes, and graphene to make things more stable and good at transferring heat without lowering their strength or weight. Even so, there are still some problems that need to be solved. There aren't any consistent rules for testing and

certifying the thermal properties of composites, which makes it harder to compare materials and use them in high-risk situations like aircraft engines or electric car propulsion systems. The high cost of high-performance fibres like carbon is another thing that keeps them from being widely used. This is especially a problem in the cost-conscious auto business. Inconsistencies in manufacturing and fiber-matrix bonding make it hard to predict the temperature, which in turn makes safety-critical systems less reliable [12]. New technologies, such as digital twin modelling and AI-driven thermal modelling, may help us figure out how to make composite designs better in the future. These technologies make it easier and cheaper than ever to guess how a material will behave in complicated thermal circumstances. A lot more electrical and thermally loaded systems are using composites. New thermal interface materials (TIMs) are helping to close the gap between the surfaces of composites and heat sinks. Thanks to the coming together of material science, modelling technology, and better ways to make things, new thermally efficient alloys will soon be made for use in cars and planes.

VI. CONCLUSION

This study used secondary sources to look into the thermal properties of modern composite materials. It brought attention to how important these materials are in the aircraft and automotive industries. The study shows that composites made of carbon, glass, and aramid fiber-reinforced plastics have a lot of different thermal behaviours. Some of these traits are uneven expansion, directional thermal conductivity, and varying levels of heat resistance and insulation. These features decide if they can be used in high-performance settings like brake systems, battery housings for electric vehicles, heat protection systems, and fuselage parts of aeroplanes. There isn't a clear winner among the composites when it comes to all thermal factors, but the results show that hybrid and application-specific designs can close the performance gap. Thermal performance is becoming more and more important in the aerospace and car industries as electric vehicles and more advanced aeronautical propulsion systems become more popular. This work stresses

even more how important secondary research is for finding innovation gaps, performance standards, and material trends that are common across the literature. More primary research is needed to prove how materials behave in real life, especially experimental studies and standardised thermal testing methods. With the help of modelling tools powered by artificial intelligence (AI), scalable production methods, and the creation of low-cost nanocomposites, the design and use of thermally optimised composite materials can be made even better.

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