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Electromagnetic Compatibility Performance of a Carbon Fiber-Based Thermal Pad for Industrial and Wearable Textile Applications

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Abstract- Carbon fiber-based heating elements are increasingly utilized in industrial and wearable textile applications due to their flexibility, lightweight structure, and uniform heat distribution. In such applications, electromagnetic compatibility (EMC) and user safety are critical performance criteria, particularly for products operating in close contact with the human body. In this study, a carbon fiber-based heating pad integrated into a textile-compatible structure was developed and experimentally evaluated in terms of radiated electromagnetic emissions and electrostatic discharge (ESD) immunity. Radiated emission measurements were conducted in accordance with EN IEC 55014-1 over the frequency range of 30 MHz to 1000 MHz. ESD immunity was assessed using contact and air discharge methods under positive and negative polarity conditions. The results demonstrate that the developed heating pad meets the relevant EMC requirements, with emission levels remaining below regulatory limits and no permanent performance degradation observed during ESD testing. These findings confirm the suitability of carbon fiber-based heating pads for industrial and wearable textile systems.

Keywords: Carbon fiber textiles, heating pad, industrial textiles, electromagnetic compatibility, radiated emission, electrostatic discharge.

I. INTRODUCTION

The widespread integration of electronic devices across numerous fields—including critical military communication systems and many civilian technologies—has led to the use of components ranging from basic circuits to highly sophisticated electronics. Modern electronic equipment inherently produces significant levels of electromagnetic interference (EMI), contributing to electromagnetic pollution that can disrupt communication networks and may pose potential risks to human well-being.

Electromagnetic interference (EMI) refers to disturbances in an electrical system that arise due to electromagnetic induction or exposure to external electromagnetic radiation. This phenomenon occurs when the electromagnetic fields of two devices interact in a way that disrupts normal operation . In addition, such electromagnetic emissions can be harmful to living organisms, as they are capable of interacting with biological tissues and potentially contributing to various health issues, including cardiovascular problems, blood-related disorders, and skin reactions. Scientists are trying developing novel materials for electromagnetic shields to protect people from severe radiation pollution.

A shield can be defined as a material or barrier that safeguards a circuit, environment, system, or the human body from harmful electromagnetic (EM) radiation. To mitigate EMI pollution, conductive and magnetic materials have been widely investigated for their effectiveness as shielding media. Such materials are commonly referred to as EMI shielding materials or microwave-absorbing materials.

Heated textile systems have become increasingly prevalent in industrial workwear, outdoor protective garments, medical therapeutic textiles, and personal thermal comfort products. These systems typically integrate electrically powered conductive elements into flexible textile structures to provide controllable heat generation. While substantial research has focused on improving the thermal efficiency, mechanical durability, and washability of such systems, considerably less attention has been directed toward their electromagnetic compatibility

(EMC) and electrical safety performance, which are critical for both user protection and reliable operation in electronically sensitive environments.

The integration of conductive heating elements into wearable textiles inherently creates potential sources of unintended electromagnetic radiation, especially under direct current (DC) or pulse-modulated power supply conditions. Moreover, the large surface area and flexible geometry of textile heaters may increase their susceptibility to electrostatic discharge (ESD), a phenomenon known to pose risks not only to embedded electronic components but also to nearby electronic systems. Prior studies on textile-based electronics and smart garments have emphasized signal integrity, antenna effects of conductive yarns, and EMI shielding behavior of fabrics; however, systematic EMC characterization of textile heating elements remains limited.

Carbon fiber is regarded as a highly promising material for EMI shielding due to its unique combination of properties, such as low density, excellent chemical and thermal stability, light weight, high flexibility, corrosion resistance, mechanical strength, and outstanding electrical conductivity. In addition, the linear morphology of the fibers enables close contact and continuity within the structure, facilitating the formation of conductive pathways. As a result, consistent and effective EMI shielding performance can be achieved. When incorporated at appropriate concentrations, carbon fibers also enhance mechanical characteristics, including compressive and flexural strength - .

Among various conductive materials used for textile heaters—such as metallic yarns, conductive polymers, silver-coated fibers, and graphene-based structures—carbon fiber has emerged as a highly promising candidate. Carbon fiber offers a unique combination of high electrical conductivity, mechanical flexibility, thermal stability, and fatigue resistance under repeated bending, making it particularly suitable for wearable and industrial textile applications. Previous research has demonstrated the superior Joule heating performance, durability, and uniform heat distribution of carbon fiber-based textile heaters. Additionally, carbon-based materials have been studied extensively for their EMI shielding and electrostatic dissipation capabilities, suggesting potential advantages for EMC performance. Despite this, the radiated emission characteristics and ESD behavior of carbon fiber heating structures integrated into textile-compatible formats have not been thoroughly investigated.

This study addresses this gap by experimentally evaluating the radiated emission and ESD performance of a carbon fiber-based heating pad specifically designed for integration into industrial and wearable textile systems. By analyzing the electromagnetic behavior of the heating structure under operational conditions, this work aims to contribute to safer and more EMC-compliant design practices for next-generation heated textile products used in proximity to sensitive electronic environments.

II. MATERIALS AND METHODS

Carbon Fiber Heating Pad Design

The heating pad developed in this study consists of a carbon fiber-based conductive layer integrated into a multilayer textile-compatible structure. The design emphasizes flexibility, low thickness, and uniform heat generation, making it suitable for incorporation into garments and industrial textile products. Electrical insulation and protective layers were applied to ensure safe operation during direct contact with the user.

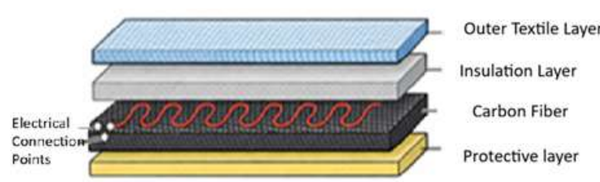

Figure1. Heating Pad Design

Radiated Emission Measurement

Radiated emission tests were conducted in compliance with the EN IEC 55014-1 standard. Measurements were performed over a frequency range of 30 MHz to 1000 MHz at a distance of 3 m using a quasi-peak detector. The heating pad was operated under normal working conditions representative of practical textile applications. Emission levels were recorded as electric field strength in dBμV/m and compared with the applicable limit values.

Radiated emission measurements were carried out in accordance with EN IEC 55014-1 under controlled experimental conditions. The antenna–device distance was set to 3 m, and measurements were performed using a BiLog antenna. The emission spectrum was scanned with a 120 kHz bandwidth, and the quasi-peak detector was employed to evaluate the emission levels in compliance with the standard requirements. The antenna polarization was configured in the horizontal orientation during the measurements to capture the worst-case radiated emission behavior of the system.(Figure 2)

Electrostatic Discharge Test

Electrostatic discharge (EN IEC 55014-2) immunity was evaluated using contact and air discharge methods. Discharges were applied at different voltage levels with both positive and negative polarity. The functional performance of the heating pad was continuously monitored during testing and re-evaluated after test completion to identify any temporary or permanent effects.

Electrostatic discharge (ESD) performance of the carbon fiber–based heating belt was evaluated under controlled environmental conditions (25.8 °C, 49.8% RH, 1000.2 hPa) using a 330 Ω / 150 pF discharge network. The specimen was subjected to direct contact, indirect contact, and air discharge modes with test levels of 2 kV and 4 kV for contact discharge, and 2 kV, 4 kV, and 8 kV for air discharge. A minimum of 200 discharges (100 positive and 100 negative) were applied with an interval of at least 1 s between pulses, covering both polarities. According to the defined performance criteria, the heating belt satisfied Criterion A after testing, indicating that the system continued to operate as intended without any functional degradation or performance loss during and after exposure to electrostatic stress. These results demonstrate that the carbon fiber heating structure exhibits strong resistance to ESD events, supporting its suitability for industrial and wearable textile applications where electrostatic exposure is likely.

III. RESULTS&DISCUSSIONS

Carbon fiber structures can also contribute to electromagnetic shielding/attenuation (EMS) through their intrinsic electrical conductivity and microstructural characteristics. The conductive carbon network promotes dielectric loss by interacting with the electric component of incident electromagnetic waves, converting part of the electromagnetic energy into heat through resistive dissipation. At the same time, the fibrous morphology and the presence of inter-fiber voids create multiple internal reflections and scattering paths, which increase the propagation distance of the waves within the material and enhance energy attenuation.

Radiated emission measurement evaluates the unintended electromagnetic energy emitted by a system during normal operation and determines whether the device behaves as an unintentional radiating source. The test is performed in a controlled anechoic environment where the electric field strength generated by the device is measured over a wide frequency range and compared with standardized EMC limits. Successfully meeting the radiated emission criteria indicates that the system does not produce harmful electromagnetic interference and that its structural and electrical configuration does not promote antenna-like radiation. This result is particularly significant for textile-integrated electronic systems, where conductive elements, wiring, and electronic components may otherwise act as radiating structures under operating conditions.

Figure 2. Radiated emission measurements of thermal pad

In the conducted measurements, it was observed that the emission values obtained at all tested frequency points remained below the limit values defined in the relevant standard. The highest measured emission level was well within a meaningful safety margin of the specified limits, and no limit exceedance was detected at any frequency.

These results indicate that the developed heating pad design does not generate harmful electromagnetic interference to its surroundings during operation and does not pose any electromagnetic compatibility issues with nearby electronic devices. (Table1) Successfully passing the radiated emission test confirms that the product meets electromagnetic compatibility requirements and can be safely used in the thermal wearable applications.

Table1. Radiated Emission Measurements

Frequency (MHz)	Measured Value (dBμV/m)	Limit (dBμV/m)	Result
181.41175	30.54	40	Pass
284.25	33.29	47	Pass
311.375	29.18	47	Pass
384.325	35.34	47	Pass
428.75	36.48	47	Pass

Figure 3. Textile integrated carbon fiber thermal pad

Tablo2. Electrostatic Discharge Test conditions and

Parameter	Value
Temperature	25.8 °C
Relative Humidity	49.8 %RH
Atmospheric Pressure	1000.2 hPa
Test Date	11.11.2025
Discharge Network (Impedance)	330 Ω / 150 pF
Discharge Types	Direct contact, Indirect contact, Air discharge
Contact Discharge Voltages	2 kV, 4 kV
Air Discharge Voltages	2 kV, 4 kV, 8 kV
Number of Discharges	≥ 200 (100 positive, 100 negative)
Polarity	Positive and Negative
Interval Between Discharges	≥ 1 s
Performance Criteria (defined)	B
Performance Result (observed)	A

Passing the electrostatic discharge (ESD) test demonstrates that the system can withstand sudden high-voltage static discharges without any functional degradation during or after exposure (Table 2). ESD events, which commonly occur due to human contact, friction between garments, or environmental conditions, can create significant potential differences on textile surfaces and pose risks to embedded electronics. Successfully meeting the ESD performance criteria indicates that the textile assembly does not allow hazardous charge accumulation and that electrostatic energy is effectively dissipated before it can interfere with the operation of the electronic components. This reflects a stable electromagnetic behavior of the system under electrostatic stress conditions and confirms its suitability for wearable and industrial applications where frequent human interaction is expected.

Considering the material composition of the thermal belt, the polyester fleece fabric itself is electrically insulating and cannot contribute to charge dissipation, while the electronic enclosure and its components are not designed to provide EMI or ESD shielding. Therefore, the observed ESD robustness of the system suggests the presence of an internal conductive pathway capable of redistributing accumulated charges. In this context, the carbon fiber heating element, even though located in a limited region of the textile structure, may act as a distributed conductive network that facilitates charge dissipation across the assembly. This behavior supports the assumption that the carbon fiber structure contributes to the electrostatic stability and overall EMC performance of the heated textile system.

The radiated emission measurements indicate that the electromagnetic emission levels of the carbon fiber-based heating pad remain below the specified limit values across the entire tested frequency range. No frequency bands exhibited emission levels exceeding regulatory thresholds.

During ESD testing, the heating pad maintained stable operation (Figure4). Although minor and temporary disturbances were observed in certain discharge events, the system recovered automatically without requiring user intervention. No permanent functional degradation or damage was detected following the completion of the ESD tests.

Figure4.Experimental validation of electromagnetic compability for thermal heating pad.

IV. CONCLUSION

The experimental results demonstrate that the carbon fiber-based heating pad exhibits favorable EMC characteristics for textile applications. The conductive properties of the carbon fiber layer, combined with the layered textile-compatible design, appear to contribute to controlled electromagnetic emission behavior. Additionally, the successful ESD immunity performance suggests that the proposed design can withstand electrostatic events commonly encountered during garment use and handling.

From an industrial textiles perspective, these findings are significant, as EMC compliance is an essential requirement for electrically active textile products intended for commercial and professional use.

In this paper, the electrical conductivity of carbon fibers enables favorable impedance matching, allowing electromagnetic waves to penetrate the material rather than being reflected at the surface, thereby improving absorption efficiency. These combined mechanisms indicate that carbon fiber heating elements may not only function as resistive heaters but also exhibit inherent electromagnetic attenuation behavior, which is directly relevant to their EMC performance in textile-based applications. This study presents an experimental evaluation of the electromagnetic compatibility performance of a carbon fiber-based heating pad designed for industrial and wearable textile applications. The heating pad successfully passed radiated emission and electrostatic discharge tests conducted in accordance with EN IEC 55014-1. The results confirm that the proposed design meets relevant EMC requirements and is suitable for integration into functional and industrial textile products.

Although the carbon fiber heating element occupies only a localized region within the thermal pad, its intrinsic electrical conductivity may contribute to charge dissipation during electrostatic discharge events. The conductive carbon network can provide localized pathways for the redistribution of accumulated surface charges, reducing the likelihood of high potential gradients across the textile structure. Therefore, it is reasonable to consider that the presence of carbon fiber may have contributed to the observed ESD robustness of the system, even though other textile layers and structural components may also play a role in the overall electrostatic behavior.

The polyester fleece (polar) fabric itself does not possess intrinsic EMI shielding capability 0-2dB) due to its electrically insulating nature. Therefore, the observed electrostatic robustness of the system cannot be attributed to the textile substrate alone and is more likely influenced by the presence of the conductive carbon fiber (20-40dB) heating element.
The power unit of the system contains several electronic and metallic components, including rechargeable batteries, a heat sink, resistive elements, a PCB, and a thermal sensor. None of these components inherently provide EMI shielding; on the contrary, PCB traces, wiring, and metallic parts may act as unintended radiating structures under operating conditions. Therefore, the low radiated emission behavior observed in the system cannot be attributed to the power electronics enclosure alone. It is reasonable to consider that the distributed conductive carbon fiber heating structure may contribute to the attenuation of localized electromagnetic fields by acting as a passive dissipative network within the textile assembly.

Consequently, the favorable radiated emission performance observed in the system may not be solely attributed to the electronic enclosure, but rather to the presence of the distributed carbon fiber heating structure, which can act as a passive electromagnetic attenuation network within the textile assembly.

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