International Journal of Health Technology and Innovation
An Official Journal of **Kalam Institute of Health Technology** | ISSN - **2583-8547**

RESEARCH ARTICLE

Carbon Comforts: The Next Frontier in Thermotherapy Yarns

Sai Kiran Goud Routhu[1], Venkata Sai Rama Pramod akula[2], Venkata Gowtham Kalla[3]

[1]Department of Medical Devices, National Institute of Pharmaceutical Education and Research, Guwahati, India.
[2]Techpod, Andhra Pradesh Medtech Zone, Visakhapatnam, India.
[3]Chief Executive Officer, World Trade Centre, Andhra Pradesh Medtech Zone, Visakhapatnam, India.

Received: 14th September, 2023; Revised: 03rd October, 2023; Accepted: 24th November, 2023; Available Online: 07th December, 2023

ABSTRACT

Thermotherapy is a therapeutic approach aimed at alleviating pain, reducing inflammation, and facilitating the wound-healing process through the controlled administration of heat via diverse methodologies. In addition to conventional hot packs and warm water compresses, a myriad of alternative heat modalities is available for therapeutic purposes. Carbon yarn is a nanofiber material that has low density high strength-to-weight ratio. The microscopic crystals of carbon bonded together in an alignment of parallel to the axis. The carbon has unique characteristics of heat resistance and electric conductivity that makes another added use of carbon yarn for thermal therapy for relieve of pain and certain inflammations by allowing the free flow of blood at the applied area. Thus, carbon also has different grades of yarn with differences in their properties and behavior on which our studies have performed for best grade selection. Carbon yarn of 12k and 24k of different lengths have undergone test for their performance. Given the equivalence in functional characteristics between electrical and thermal conductivity, our material selection approach places paramount importance on factors such as electrical efficiency and resistance to high temperatures. This meticulous consideration ensures the creation of an unparalleled and exemplary thermal therapy product. The test outcomes for these carbon yarn samples under various power supply settings have yielded divergent results, yet a notable trend emerges an accelerated heating rate with an increase in current (Amp) while maintaining a constant voltage. The temperature at constant voltage remains the same with the fluctuations of ± 2°C/min. The objective is to identify a material characterized by minimal electricity consumption and concurrent high-temperature release. Another remarkable attribute of this material is its exceptional ability to rapidly cool to room temperature upon the removal of the power supply. The heat transfer mechanisms, both convective and radiative, exhibited a diminishing trend as the length and number of tows of the simulated carbon fibre electric heating wire increased. Particularly noteworthy was the substantial dominance of convective heat transfer over radiative heat transfer, unequivocally highlighting convective heat transfer as the primary mode for dissipating heat in the carbon fibre electric heating wire.

Keywords: Carbon Yarn, 12k and 24k grade, Heat Conductivity, Electricity Consumption, Heat Transfer, Yarn Length and Thickness.

International Journal of Health Technology and Innovation (2023)

How to cite this article: Routhu SKG, Akula VSRP, Kalla VG. Carbon Comforts: The Next Frontier in Thermotherapy Yarns. International Journal of Health Technology and Innovation. 2023;2(3):21-26.

Doi: 10.60142/ijhti.v2i03.05

Source of support: Nil.

Conflict of interest: None

INTRODUCTION

Thermotherapy encompasses an advanced regimen for the amelioration of pain, mitigation of inflammatory responses, and expeditious wound healing, achieved by the deliberate application of heat through a multifarious array of techniques. Beyond the commonplace utilization of hot packs and heated water compresses, a panoply of innovative and specialized heat-delivery methodologies is available for the purpose of therapeutic intervention.[1] From the plethora of available heat delivery modalities, our discerning choice gravitates toward expeditious heat application and impeccable uniformity in heat dispersion across the treatment area. Our selected approach not only expedites the warming process but also guarantees precision in delivering heat to the critical regions where unobstructed blood flow is imperative. Numerous thermally and electrically conductive materials and elements are employed with the primary purpose of generating controlled heat to expedite the wound-healing process and alleviate inflammation. The secondary objective of this heating method is to emit heat in the form of controlled waveforms or radiation,

**Author for Correspondence: saikiranrouth10@gmail.com*

while ensuring absolute safety and compatibility with various materials, without any adverse effects on the human body.[2] The exceptional attributes of carbon have directed our attention toward fibre materials derived from carbon through diverse processes, transforming them into microscopic crystal fibers characterized by robust intermolecular bonds.[3]

Carbon fibers are meticulously crafted from polyacrylonitrile (PAN) filaments, showcasing extraordinary attributes. These fibers possess a low density, an impressive strength-to-weight ratio, robust mechanical integrity, and exceptional resistance to chemical degradation.[4] The yarn is stratified into multiple grades, delineated by the filament count within each tow, spanning from 3K to 48K filaments, each manifesting unique behavior in response to electrical power. For our research endeavors, we have opted to employ carbon yarns of the 12k and 24k grades.[3] Upon connecting the carbon yarn to the power supply, the carbon molecules within the heater undergo dynamic interactions, resulting in the phenomenon of "Brownian motion."[5] The heat generated from these molecular collisions is primarily transmitted through the avenues of thermal convection and radiant energy transfer.[6] One of the paramount safety advantages associated with heat therapy employing these yarns is their non-invasive nature, as they emit heat in the form of far-infrared radiation, a modality known for its inherent benefits to human well-being, without any harmful effects.

Analogous to resistive metals, which produce a periodic electromagnetic wave field upon being electrified due to their inherent properties as heating elements,[7] responsible for the radiative heat release we previously discussed as a means of ensuring even heat distribution, our carbon yarn similarly possesses this property when subjected to electrical activation. The fundamental principles of physics[8] governing the interplay between electrical current, resistance, length, and thickness provide a foundational framework to elucidate the behavior of carbon in response to a power supply, leveraging the characteristics we discussed earlier.[9] Standardized testing of carbon yarn samples, sharing identical thickness but representing two distinct grades namely, 12k and 24k was undertaken using lengths of 7, 12, and 16 cm. These specimens were subjected to a 12v power supply, with the current varying across a range from 0.1 to 1 Amp for comprehensive assessment. The temperature variations induced by electrification were meticulously monitored utilizing an infrared (IR) thermometer. In addition to individual tests, we conducted experiments by configuring the carbon yarn in both series and parallel connections, all under the constant application of 12 V with varying current levels, to comprehensively assess their performance.

The core objective of this application is the investigation of heat release characteristics exhibited by carbon fiber electric heating wires. In the arena of thermal testing methodologies, global scholars have harnessed the power of digital holographic interferometry (DHI) to meticulously examine crucial heat transfer parameters. Notably, in the research conducted by Kumar,[10,11] a deep dive was undertaken to measure the local convective heat transfer coefficient (h) along the surface of vertically oriented electrically heated wires, employing DHI. This comprehensive experimentation encompassed wires of varying diameters, and the acquired data consistently fell within the established range delineated in prior literature. Furthermore, the research extended its purview to the measurement of local heat flux Q(y) and convective heat transfer coefficient (*hc*) along the surface of electrically heated wires, again leveraging DHI. These investigations involved tungsten wires with differing diameters. In addition, supplementary studies presented their findings on experimental inquiries related to the heat dissipation processes of plate-fin heat sinks, all examined through the lens of DHI. Additionally, Masashi Ishikawa's[12] work delved into the realm of active thermographic non-destructive inspection, employing innovative laser scanning methodologies for a fresh perspective on this subject matter.

While a multitude of scholars have extensively researched carbon fiber materials and their diverse applications, a noticeable gap exists when it comes to exploring the thermal applications of electrified carbon fibre materials, particularly in relation to the performance nuances among carbon grades that, while serving similar functions, exhibit distinctive outcomes during testing. Furthermore, the intricate relationship between the temperature response of carbon fiber materials to electrical stimulation, particularly concerning varying lengths, remains conspicuously underrepresented in existing literature.[13] This knowledge void becomes especially pertinent when considering the utilization of carbon yarn in diverse temperature environments for the optimization of thermal comfort. As a result, we embarked on an experimental investigation to scrutinize the exothermic behavior of carbon yarn, filling a notable void in the scholarly discourse.

MATERIAL AND METHODS

In this experiment the carbon fibre yarn of 12k and 24k grades with various length range from 7 to 16 cm had opted for the test and the parameters for electrifying the yarn taken are as follows:

- Length of yarn
- Temperature
- Voltage
- Current
- Resistance
- Thickness

TESTING METHODOLOGY

Our experimental configuration involved the connection of carbon yarns of differing lengths to a power supply. These yarns were situated atop a paper surface. In order to capture the temperature dynamics comprehensively, we strategically positioned infrared (IR) thermometers to monitor and record temperature variations both on the paper's surface and along the length of the yarn.[14] This setup allowed us to gain valuable insights into the thermal behavior of both the carbon yarn and its immediate environment.

Measurements

Our study encompassed a thorough investigation of heating power, surface temperature, and power consumption attributes for carbon yarns featuring different tows (12k and 24k) and varying lengths (ranging from 7 to 16cm). This examination aimed to discern the factors contributing to achieving elevated temperatures under specific voltage and current parameters

Measuring Instruments

For our research, we harnessed the capabilities of a power supply unit equipped with voltage and current parameter measuring features, specifically the Keithley 2231a-30-3 Triple Channel Dc Power Supply. In addition, we utilized a K type thermoelectric couple thermometer in tandem with a temperature measuring probe and an IR thermometer (Fluke 62 MAX+ IR thermometer) to comprehensively monitor both yarn and surface temperatures. Notably, to maintain the precision and reliability of our data, we rigorously calibrated all of these instruments prior to commencing our experiments.

Procedure

The carbon fiber yarns of varying lengths were meticulously positioned atop a flat sheet of paper, with each yarn having an individual connection to the power supply, as illustrated in Figure 1. To facilitate our measurements, testing instruments were interconnected for data collection. A thermocouple was employed to record temperature fluctuations resulting from changes in power supply voltage and current in amperes, and these measurements were taken at multiple points along the length of the carbon fiber yarn.[15] These measurement points were evenly distributed across the yarn's length to ensure comprehensive data collection. Concurrently, an infrared (IR) thermometer was deployed to assess the distribution of temperature effects in the surrounding area of the carbon yarn on the sheet.

The schematic in the provided figure illustrates the independent connections of carbon yarn fibers to the power supply unit and thermocouples for precise temperature monitoring. We systematically manipulated the current input to investigate its influence on varying voltage levels. Moreover, we introduced a time component to evaluate the yarn's heating speed in response to increasing current and its ability to maintain a stable temperature for approximately 20 to 30 minutes. Subsequently, as we powered down the supply, we recorded the temperature drop back to ambient room temperature. This extensive dataset was collected and subjected to thorough analysis

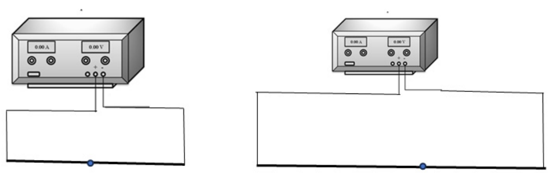

Fig 1: Represents the carbon fibre yarn connected to power supply unit of a) 7 cm length b)12 cm length. The point on fibre length is reference point for temperature measurement by thermocouple

Parameters

The parameters of carbon fibre yarn and its properties of different grade are list in the Table 1.

Boundary Conditions And Governing Equations

The conductivity of carbon fiber depends on the parameters of length, thickness, resistance offered. According to ohm law

$$R = \rho L/A \qquad (1)$$

Here as the length increases resistance to conductivity increases.

Ohm's law also states that

$$V = IR \qquad (2)$$

As the length of an electrical conductor increases, a corresponding voltage increment is necessary to sustain the desired output. Likewise, a lengthened conductor generally necessitates an increase in current to achieve the intended performance level.[15] Furthermore, the electrical conductivity and current consumption are both modulated by the conductor's length and thickness. This interplay ultimately dictates the rate of heat dissipation when current is introduced.

Heat dissipation is given by:

$$P = I^2 R \qquad (3)$$

This equation, succinctly encapsulates the direct proportionality between power dissipation (P) in a resistor and two critical variables: the square of the current (I) flowing through it and the resistance (R) it offers. It elegantly illustrates the fundamental principle that when electric current traverses a resistor, it invariably generates heat. The quantity of heat produced is intricately tied to the magnitude of the current and the resistance intrinsic to the component.

When electricity is applied to carbon fiber yarn, it expels heat through a combination of thermal convection and radiation. Consequently, boundary conditions are meticulously configured in alignment with the principles of thermal convection and radiation.[14] The governing boundary equation for surface radiative heat transfer is articulated as follows:

$$q_r = \varepsilon\sigma(T_s^4 - T_w^4) \qquad (4)$$

Here, we have q_r representing the radiative heat flux, ε as the emissivity of the material, σ as the thermal radiation constant of the blackbody, T_s for the surface temperature of the launching surface, and T_w for the wall temperature. The boundary equation for convective heat flux is expressed as follows:

$$q_c = h(T_S - T_a) \qquad (5)$$

where q_c is the convective heat flux, h is the convective heat transfer coefficient, and T_a is the air temperature.

In the context of the experiment, we strategically choose the length and thickness of the carbon yarn based on the

Table 1: properties of different grade carbon fibre yarn

Fiber type	*Number of filaments*	*Yield tex (g/1000m)*	*Tensile strength*		*Tensile modulus*		*Elongation (%)*	*Density (g/cm³)*	*Filament diameter (µ)*
			Ksi	*MPa*	*Msi*	*GPa*			
TC-36s 12K	12000	800	710	4900	36	250	2.0	1.81	7
TC-36s 24K	24000	1600	710	4900	36	250	2.0	1.81	7

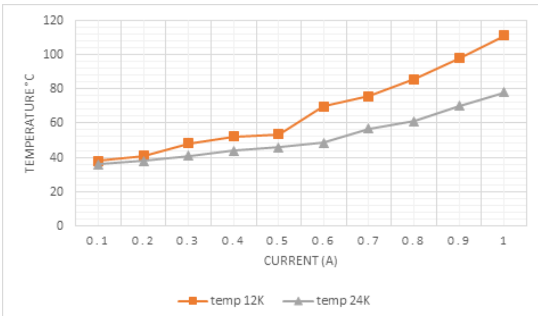

Figure 2: The comparison between the 12K and 24K grade carbon yarn is conducted by subjecting them to a power supply with a current range varying from 0.1 to 1 Amp. This analysis aims to discern the differential behaviour and performance of these two grades under varying current conditions

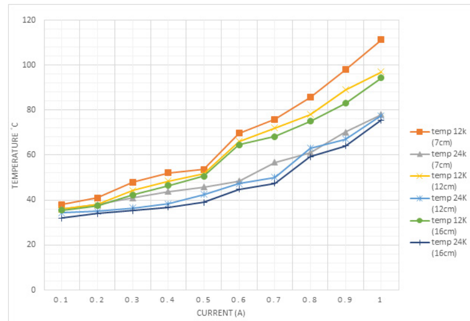

Figure 3: The heating rate, observed in both 12K and 24K grade carbon yarn, spanning various lengths and subjected to diverse power supply parameters, can be summarized

equations provided. This selection was made with the goal of enhancing thermal therapy, seeking to achieve efficient heat dissipation while minimizing power consumption. Both grades of the material, differing in length, were carefully selected and connected to a power source. They were positioned on a sheet surface, and the dispersion of heat in the surrounding area was observed using an IR thermometer.

RESULTS

The surface temperature of the carbon yarn was scrupulously scrutinized as it underwent electrification, with nuanced variations in current input under the steadfast presence of a consistent voltage, all within a predetermined temporal threshold. In strict adherence to the aforementioned boundary parameters, we assiduously documented the empirical data, thereby establishing the groundwork for an exhaustive and intricately detailed comparative analysis.

Figure 2 visually illustrates the comparative analysis between the 12K and 24K grade carbon yarn. These two grades exhibit distinct thermal conductivity behaviors when connected to a power supply. The conductivity of both yarn types allows for a temperature range spanning from 30 to 120°C under the influence of a 1 Amp electric supply.

Figure 3, we delve into a thorough comparative analysis of the electrical conductivity characteristics exhibited by both 12K and 24K grade carbon yarns. Throughout these tests, a diverse array of yarn lengths were subjected to a constant voltage while the current was varied. An intriguing pattern emerges: the temperature of the yarn directly responds to changes in the power supply. Furthermore, a consistent trend prevails, where an increase in yarn length yields a commensurate rise in temperature, all within the context of a constant voltage and uniform current across the spectrum of yarn samples. As an exemplar, when electrifying a 16cm length of 12K carbon yarn, it undergoes a rapid temperature surge from ambient conditions to 80°C within an impressively brief interval of 30 to 40 seconds, all under a 0.8 Amp power supply.[16] Furthermore, upon deactivation of the power supply, the yarn efficiently reverts to ambient temperature in less than 60 seconds. Most notably, the yarn achieves stabilization at a consistent temperature of 85 ± 4°C within a mere 2-minute timeframe, sustaining this thermal equilibrium for a continuous 20-minute duration. It's worth emphasizing the yarn's commendable radiative heat dissipation at the applied surface and throughout its immediate vicinity. Similarly, the 24K grade carbon yarn underwent an experiment of equal voltage and length, resulting in a temperature increase to 68 ± 3°C in under 2 minutes. Remarkably, this stable temperature was maintained consistently for a continuous 20-minute period. Notably, when the power supply was turned off, the cooling rate closely paralleled that of the 12K grade yarn. The experimental data across various yarn lengths (7cm, 12cm, and 16cm) revealed distinct temperature elevations for each applied power supply, throughout the experiments, it became evident that the heating rates for the designated lengths displayed the following values: 80, 76, and 73°C/minute for the 12K grade yarn, while the 24K grade yarn exhibited rates of 65, 63, and 58°C/minute for the same lengths. This observation highlights a discernible pattern wherein an increase in yarn length corresponds to a reduction in the heating rate, even when the yarns belong to the same tow and share the same grade of carbon material. These results underscore the unique feature of this yarn—it exhibits exceptional rapid heating and cooling characteristics while operating with minimal power consumption. This quality makes it an ideal choice for applications in thermal therapy and wearable comfort, effortlessly powered by direct current (DC) voltage.

The surface stabilization temperatures of carbon fibre yarn, varying in tows and lengths (7, 12, and 16 cm), revealed discernible discrepancies. Notably, for the 12K grade, these temperatures registered at 88, 81, and 78°C, respectively. In contrast, the 24K grade demonstrated lower values of 64, 58, and 51°C under corresponding conditions. This observation accentuates a compelling pattern: a reduction in surface stabilization temperature occurs concomitantly with an increase in yarn length. Furthermore, in identical scenarios, the 12K yarn consistently maintained higher temperature levels in comparison to its 24K counterpart. At a DC power supply of 6V and 0.8 Amp, a notable discrepancy of 26°C was observed, with the stable temperature of the 16cm length 12K carbon yarn surpassing that of the 24K counterpart. This analysis accentuates the unique capacity of different types and specifications of carbon fibre yarn to uphold distinct constant temperatures under the influence of electrification. Consequently, these findings carry significant implications, especially in the domain of power supply optimization, where the minimization of heat required for therapeutic applications in cold climates and managing inflammatory conditions can be efficiently achieved through the judicious application of these outcomes, particularly in the design and development of wearable technologies incorporating this innovative yarn.

DISCUSSION

The core focus of our experimentation revolves around optimizing power supply efficiency, and in this context, the carbon yarn emerges as a standout. Diverging from conventional heating materials, it distinguishes itself through its exceptional capability for swift and precise heating and cooling when electrified at low voltage. Hence, the unique properties of carbon yarn make it a suitable candidate not only for applications in aerospace but also for integration into wearable designs. With diverse grades of carbon at our disposal for experimentation, it opens up a myriad of possibilities for textile-based wearables designed to accommodate various functional activities. Here, our central emphasis was placed on the assessment of electrical and thermal conductivity, specifically geared toward the potential application of thermotherapy in cost-effective, small-quantity wearable devices. The carbon yarn underwent prolonged electrification under stable voltage conditions with varying current supplies, spanning an extended duration. This comprehensive evaluation aimed to gauge its resilience and tensile strength in the face of continuous heating while considering both high and low-voltage scenarios. Furthermore, we meticulously observed the material's behavior upon the cessation of power supply.

CONCLUSION

The extensive examination of carbon fibre yarn's heating properties and conductivity attributes encompassed a thorough exploration of various yarn lengths across two distinct filament tow grades-specifically, 12K and 24K. The results of these experiments revealed that the carbon yarn exhibited a remarkable capacity for rapid electrification, swiftly ascending to a peak temperature of 110°C in less than 2 minutes, all under a modest power supply of 6V and 0.8 Amp. Equally impressive was the yarn's ability to sustain this consistent temperature for an astonishing 20-minute duration under the same power supply conditions, followed by a rapid cooldown to room temperature in less than a minute upon power supply deactivation. These empirical findings not only underscore the carbon yarn's commendable performance in both electrical and thermal conductivity but also highlight the proportional decrease in heating rate with increasing yarn length. Notably, the 12K yarn consistently outperformed its 24K counterpart in heating rate, even when their lengths were equal.

The carbon fiber yarn showcased remarkable thermal stability, with its surface temperature remaining virtually constant during extended electrification experiments. Nevertheless, it's important to emphasize that the surface stability temperature exhibited variations dependent on the tow number and length—generally declining with longer lengths. Furthermore, when comparing yarns of equivalent length, the 12K variant consistently outperformed the 24K yarn by maintaining a higher surface stability temperature. Additionally, a clear correlation emerged, indicating that as the length increased, the heating power of the carbon fiber yarn notably decreased.

ACKNOWLEDGMENTS

This study is supported by the National Institute of Pharmaceutical Education and Research, Guwahati and Andhra Pradesh Medtech Zone. I would like to extend my heartfelt thanks to Dr. Radhakrishnanand P, Professor, and Suraj naik who contributed to the success of this experiment. Your support and collaboration were invaluable

DATA AVAILABILITY STATEMENT

The data in Figures 2 and 3 are the data from the experimental results. The (1)-(5) are derived from basic physics data of electricity and its conductivity fundamental principles.

REFERENCES

1. Brosseau L, Yonge K, Robinson V, Marchand S, Judd M, Wells G, et al. Thermotherapy for treatment of osteoarthritis. Physiotherapy. 2003;89(12):694–5.
2. Bahadir SK, Sahin UK. A Wearable Heating System with a Controllable e-Textile- Based Thermal Panel. Wearable Technol. 2018;
3. Envisions C, Hub K, Information IC. Practical and Insightful Composites Information Composite Reinforcements : Carbon Fiber Fiberglass Kevlar / Aramid Composite Reinforcements. 2022;
4. Li J, Cao C, Zhu H. Synthesis and characterization of graphite-like carbon nitride nanobelts and nanotubes. Nanotechnology. 2007;18(11).
5. Cecconi F, Cencini M, Falcioni M, Vulpiani A. Brownian motion and diffusion: From stochastic processes to chaos and beyond. Chaos. 2005;15(2).
6. Tattersall GJ. Infrared thermography: A non-invasive window into thermal physiology. Comp Biochem Physiol -Part A Mol Integr Physiol [Internet]. 2016;202:78–98. Available from: http://dx.doi.org/10.1016/j.cbpa.2016.02.022
7. Athanasopoulos N, Koutsoukis G, Vlachos D, Kostopoulos

V. Temperature uniformity analysis and development of open lightweight composite molds using carbon fibers as heating elements. Compos Part B Eng [Internet]. 2013;50:279–89. Available from: http://dx.doi.org/10.1016/j.compositesb.2013.02.038

8. Yan L, Zheng YB, Zhao F, Li S, Gao X, Xu B, et al. Chemistry and physics of a single atomic layer: Strategies and challenges for functionalization of graphene and graphene-based materials. Chem Soc Rev. 2012;41(1):97–114.
9. Chimsa J, Seechaipat T, Senavongse W. Design and development of massage therapy device for arm. BMEiCON 2017 - 10th Biomed Eng Int Conf. 2017;2017-Janua:1–5.
10. Kumar V, Shakher C. Study of heat dissipation process from heat sink using lensless Fourier transform digital holographic interferometry. Appl Opt. 2015;54(6):1257.
11. Kumar V, Kumar M, Shakher C. Measurement of natural convective heat transfer coefficient along the surface of a heated wire using digital holographic interferometry. Appl Opt. 2014;53(27):G74.
12. Ishikawa M, Ando M, Koyama M, Nishino H. Active thermographic inspection of carbon fiber reinforced plastic laminates using laser scanning heating. Compos Struct [Internet]. 2019;209:515–22. Available from: https://doi.org/10.1016/j.compstruct.2018.10.113
13. Santangelo PE, Santunione G, Muscio A. Experimental methodology for quantitative assessment of heat-wrap thermal transient behavior. Med Eng Phys [Internet]. 2019;69:72–84. Available from: https://doi.org/10.1016/j.medengphy.2019.05.003
14. Zhao HB, Dai JA, Wu K, Kong FH. Experimental and modeling analysis of thermal characteristics in carbon fiber wires. Heat Transf [Internet]. 2020;49(4):1863–76. Available from: http://dx.doi.org/10.1002/htj.21697
15. Coordinating S, Insulation E. IEEE Std 99™-2007, IEEE Recommended Practice for the Preparation of Test Procedures for the Thermal Evaluation of Insulation Systems for Electrical Equipment. 2008;2007(February).
16. Tan Y, Zhu Y, Xiao H. Model Experimental Study of Carbon Fiber Heating Wire for Deicing and Snow Melting on a Bridge Deck. Adv Civ Eng. 2020;2020.