ELECTROMAGNETIC INTERFERENCE SHIELDING AND JOULE HEATING PROPERTIES OF ACTIVATED CARBON FABRICS

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Electromagnetic Interference Shielding and Joule Heating Properties of Activated Carbon Fabrics

by

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Dedicated to my parents, brother, wife, and daughter, who have always been a constant source of support and encouragement in my life.

Certificate

This is to certify that the thesis entitled "**Electromagnetic Interference Shielding and Joule Heating Properties of Activated Carbon Fabrics**" being submitted by **Mr. Kuldip Singh** to the Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy** is a record of bona fide research work carried out by him in the Department of Textile and Fibre Engineering, Indian Institute of Technology Delhi. Kuldip has worked under my guidance and supervision and has fulfilled the requirements for submitting this thesis, which to our knowledge has reached the requisite standard. The results contained in this thesis are original and have not been submitted, in part or full, to any other university or institute for the award of any other degree or diploma.

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Declaration by the Author

This thesis comprises my original work and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution of others in jointly authored works, which I have included in my thesis.

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Abstract

Recently, the activated carbon fibres gained significant importance due to their wide range of pore size distribution, well-developed internal porous network, and greater specific surface area. However, the major concerns for further advancements of activated carbon fibres in other applications are their poor structural, physical, and handling properties. The research work performed in this thesis deals with improving the physical, and handling properties of activated carbon fabrics besides finding new applications in EMI shielding and joule heating.

In the first study, the Kevlar-fibre derived woven activated carbon fabrics were produced using single-stage carbonization and physical activation method. The Box-Behnken design and response surface methodology were employed for the optimization of three process parameters (i.e. charcoal amount, nitrogen gas flow rate, and carbonization temperature) to get high carbon yield and low electrical resistivity of activated carbon fabrics. An optimum amount of charcoal, optimum nitrogen flow rate, and low carbonization temperature were found to provide higher carbon yield. On the other hand, low charcoal amount, high carbonization temperature, and optimum nitrogen flow rate produced low electrical resistivity. Further, the optimized sample of low electrical resistivity showed higher EMI shielding than the other sample of high carbon yield.

In the second study, the effect of fabric type (i.e. woven and needlepunched nonwoven) of Kevlar fibres was investigated for physical, structural, electrical, EMI shielding, and joule heating properties of activated carbon fabrics. The Kevlar woven fabric derived activated carbon fabrics showed better physical and mechanical properties, however lower electrical properties as compared to the Kevlar nonwoven fabric derived activated carbon fabrics. The higher EMI shielding, and better joule heating properties were found in the case of nonwoven activated carbon fabrics than the woven activated carbon fabrics.

In the third study, the effect of fibre type (i.e. semicrystalline polyacrylonitrile PAN fibres and highly crystalline Kevlar fibres) was investigated for physical, structural, electrical, EMI shielding, and joule heating properties of nonwoven activated carbon fabrics. The greater carbon yield, low dusting tendency, better mechanical as well as electrical properties were found in case of PAN fibre-derived activated carbon fabrics. However, enhanced flexibility and better shrinkage properties were seen in case of Kevlar fibre-derived activated carbon fabrics. The EMI shielding properties were found to increase with the carbonization temperature for both PAN and Kevlar fibre-derived activated carbon fabrics. Further, the Kevlar fibre-derived activated carbon fabrics showed faster heating, more heating efficiency, and rapid cooling, but at an increased voltage of 5V than 3V of PAN-derived activated carbon fabric.

In the fourth study, PAN and Kevlar fibres were blended in different proportions to study the effect of fibre blending on the physical, structural, electrical, EMI shielding, and joule heating properties of nonwoven activated carbon fabrics. Higher carbon yield, reduced dusting tendency, and improved mechanical and electrical properties were observed for the PAN-rich activated carbon fabrics. The Kevlar-rich activated carbon fabrics showed better flexibility and minimum shrinkage. Further, PAN-rich carbonized fabrics exhibited superior EMI shielding and better joule heating properties.

In the fifth study, the effect of layering of metalized fabric on physical, structural, electrical, EMI shielding, and joule heating properties of nonwoven activated carbon fabrics was studied. The metalized fabric individually showed relatively higher EMI shielding, but poor prolonged heating performance due to burning. On the contrary, the activated carbon fabrics depicted relatively lower EMI shielding, but robust joule heating properties without any burning. Nevertheless, the layered structure of activated carbon fabric with metalized fabric showed stronger EMI shielding and robust joule heating performance because of enhanced absorption-reflection-reabsorption of the electromagnetic waves.

सार

हाल ही में, सक्रिय कार्बन फाइबर को उनके छिद्र आकार वितरण की विस्तृत श्रृंखला, अच्छी तरह से विकसित आंतरिक छिद्रपूर्ण नेटवर्क और अधिक विशिष्ट सतह क्षेत्र के कारण महत्वपूर्ण महत्व प्राप्त हुआ है। हालाँकि, अन्य अनुप्रयोगों में सक्रिय कार्बन फाइबर की आगे की प्रगति के लिए प्रमुख चिंताएँ उनकी खराब संरचनात्मक, भौतिक और हैंडलिंग गुण हैं। इस थीसिस में किया गया शोध कार्य ईएमआई परिरक्षण और ओमिक हीटिंग में उनके नए अनुप्रयोगों को खोजने के अलावा सक्रिय कार्बन कपड़ों के भौतिक और हैंडलिंग गुणों में सुधार से संबंधित है।

पहले अध्ययन में, केवलर-फाइबर व्युत्पन्न बुने हुए सक्रिय कार्बन कपड़े नव विकसित एकल-चरण कार्बोनाइजेशन और भौतिक सक्रियण विधि का उपयोग करके उत्पादित किए गए थे। उच्च कार्बन उपज और सक्रिय कार्बन कपड़ों की कम विद्युत प्रतिरोधकता प्राप्त करने के लिए तीन प्रक्रिया मापदंडों (यानी चारकोल की मात्रा, नाइट्रोजन गैस प्रवाह दर और कार्बोनाइजेशन तापमान) को अनुकूलित करने के लिए बॉक्स-बेनकेन डिजाइन और प्रतिक्रिया सतह पद्धति को नियोजित किया गया था। उच्च कार्बन उपज प्रदान करने के लिए चारकोल की इष्टतम मात्रा, इष्टतम नाइट्रोजन प्रवाह दर और कम कार्बोनाइजेशन तापमान पाया गया। दूसरी ओर, कम चारकोल मात्रा, उच्च कार्बोनाइजेशन तापमान और इष्टतम नाइट्रोजन प्रवाह दर ने कम विद्युत प्रतिरोधकता उत्पन्न की। इसके अलावा, कम विद्युत प्रतिरोधकता के अनुकूलित नमूने ने उच्च कार्बन उपज के अन्य नमूने की तुलना में उच्च ईएमआई परिरक्षण दिखाया।

दूसरे अध्ययन में, सक्रिय कार्बन कपड़ों के भौतिक, संरचनात्मक, विद्युत, ईएमआई परिरक्षण और ओमिक हीटिंग गुणों के लिए केवलर फाइबर के कपड़े के प्रकार (यानी बुने हुए और सुई-छिद्रित गैर-बुने हुए) के प्रभाव की जांच की गई। बुने हुए सक्रिय कार्बन कपड़ों ने बेहतर भौतिक और यांत्रिक गुण दिखाए, हालांकि गैर बुने हुए सक्रिय कार्बन कपड़ों की तुलना में कम विद्युत गुण दिखाए। बुने हुए सक्रिय कार्बन कपड़ों की तुलना में गैर बुने हुए सक्रिय कार्बन कपड़ों के मामले में उच्च ईएमआई परिरक्षण और बेहतर ओमिक हीटिंग गुण पाए गए।

तीसरे अध्ययन में, गैर बुने हुए सक्रिय कार्बन कपड़ों के भौतिक, संरचनात्मक, विद्युत, ईएमआई परिरक्षण और ओमिक हीटिंग गुणों के लिए फाइबर प्रकार (यानी अर्ध-क्रिस्टलीय पॉलीएक्रिलोनिट्राइल पैन और अत्यधिक क्रिस्टलीय केवलर फाइबर) के प्रभाव की जांच की गई। पैन-व्युत्पन्न सक्रिय कार्बन फैब्रिक ने उच्च कार्बन उपज, कम धूल की प्रवृत्ति, बेहतर यांत्रिक और विद्युत गुण प्रदान किए; तथापि केवलर व्युत्पन्न सक्रिय कार्बन कपड़ों की तुलना में खराब लचीलापन और सिकुड़न गुण। पैन और केवलर फाइबर व्युत्पन्न सक्रिय कार्बन फैब्रिक दोनों के लिए कार्बोनाइजेशन तापमान के साथ ईएमआई परिरक्षण गुणों में वृद्धि पाई गई। इसके अलावा, केवलर फाइबर व्युत्पन्न सक्रिय कार्बन फैब्रिक ने तेजी से हीटिंग, उच्च विद्युत ताप दक्षता और तेज शीतलन प्रदर्शन दिखाया, लेकिन पैन व्युत्पन्न सक्रिय कार्बन फैब्रिक के 3V की तुलना में 5V के बढ़े हुए वोल्टेज पर।

चौथे अध्ययन में, गैर बुने हुए सक्रिय कार्बन कपड़ों के भौतिक, संरचनात्मक, विद्युत, ईएमआई परिरक्षण और जूल हीटिंग गुणों पर फाइबर मिश्रण के प्रभाव का अध्ययन करने के लिए पैन और केवलर फाइबर को अलग-अलग अनुपात में मिश्रित किया गया था। पैन-समृद्ध सक्रिय कार्बन कपड़ों के लिए उच्च कार्बन उपज, कम धूल की प्रवृत्ति और बेहतर यांत्रिक और विद्युत गुणों को देखा गया। केवलर-समृद्ध सक्रिय कार्बन कपड़ों ने बेहतर लचीलापन और न्यूनतम संकोचन दिखाया। इसके अलावा, पैन-समृद्ध कार्बोनाइज्ड कपड़ों ने बेहतर ईएमआई परिरक्षण और बेहतर जूल हीटिंग गुणों का प्रदर्शन किया।

पांचवें अध्ययन में, गैर बुने हुए सक्रिय कार्बन कपड़ों के भौतिक, संरचनात्मक, विद्युत, ईएमआई परिरक्षण और जूल हीटिंग गुणों पर धातुकृत कपड़े की परत के प्रभाव का अध्ययन किया गया था। धातुयुक्त कपड़े ने व्यक्तिगत रूप से अपेक्षाकृत उच्च ईएमआई परिरक्षण दिखाया, लेकिन जलने के कारण लंबे समय तक हीटिंग प्रदर्शन खराब रहा। इसके विपरीत, सक्रिय कार्बन कपड़े अपेक्षाकृत कम ईएमआई परिरक्षण, लेकिन बिना किसी जलन के मजबूत जूल हीटिंग गुणों को दर्शाते हैं। फिर भी, धातुयुक्त कपड़े के साथ सक्रिय कार्बन कपड़े की स्तरित संरचना ने विद्युत चुम्बकीय तरंगों के बेहतर अवशोषण-प्रतिबिंब-पुनर्अवशोषण के कारण मजबूत ईएमआई परिरक्षण और मजबूत ओमिक हीटिंग प्रदर्शन दिखाया।

List of Journal Publications

1 Kuldip Singh, and Vijay Baheti. "Structure-property relationship of carbonized needlepunched nonwovens for electromagnetic interference shielding and ohmic heating applications." ***Synthetic Metals*** 292 (2023): 117220.

2 Kuldip Singh, and Vijay Baheti. "Electromagnetic interference shielding and ohmic heating applications of carbonized nonwoven fabrics prepared from blended fibrous wastes." ***Diamond and Related Materials*** (2023): 109708.

3 Kuldip Singh, and Vijay Baheti. "Electromagnetic interference shielding and ohmic heating of layered structures of activated carbon fabric and metalized fabric." ***Synthetic Metals*** 298 (2023): 117439.

4 Kuldip Singh, and Vijay Baheti. "Optimum carbonization of Kevlar fabric for electromagnetic interference shielding applications." ***The Journal of The Textile Institute*** (2023): 1-11.

List of International Conferences

1. Kuldip Singh, and Vijay Baheti; Effect of carbonization temperature on the fibrous nonwoven structures for joule heating applications, **3rd International Conference on Functional Textile and Clothing (FTC 2023)**, 10th - 12th February 2023 held at IIT Delhi, New Delhi, India.
2. Kuldip Singh, Vijay Baheti; A strategy to improve the electromagnetic interference shielding of activated carbon fabric using metalized fabric; **3rd International Conference on Emerging Trends in Traditional and Technical Textiles (ICETT-2023)**, 28th-30th April 2023 held at NIT Jalandhar, India.
3. Kuldip Singh, Vijay Baheti; Optimum conditions for the carbonization of Kevlar fabric for electromagnetic interference shielding; **The 92nd Textile Institute World Conference (TIWC 2023)**, 3rd-6th July 2023, held at University of Huddersfield, Huddersfield, UK.

Table of Contents

List of Figures

List of Tables

Abbreviations

A	Absorption coefficient
AC	Acrylic based activated carbon fabrics
ASTM	American Society for Testing and Materials
BET	Brunauer, Emmett and Teller
CH	Charcoal amount
CT	Carbonization temperature
EDX	Energy dispersive X-ray spectroscopy
EM	Electro-magnetic
EMI SE	Electromagnetic interference shielding effectiveness
EMI	Electromagnetic Interference
EPI	Ends per inch
GAC	Granular activated carbon
GF	Gas flow rate
KV	Kevlar-based activated carbon fabrics
MC	Metalized cotton
PAC	Powdered activated carbon
PAN	Polyacrylonitrile
PPI	Picks per inch
R	Reflection coefficient
SE	Shielding effectiveness
SE_A	Shielding effectiveness due to absorption
SEM	Scanning electron microscopy
SE_R	Shielding effectiveness due to reflection
SE_T	Total shielding effectiveness
T	Transmission coefficient
XRD	X-ray diffraction

List of Symbols

%	Percentage
ρ_s	Surface resistivity
ρ_v	Volume resistivity
$<$	Less than
$>$	Greater than
h_{r+c}	Heat transferred due to radiation and convection
σ	Electrical conductivity
τ_d	Decay time constant
τ_g	Growth time constant