

**ELECTROTHERMAL CHARACTERIZATION OF  
CONDUCTIVE YARN-INTEGRATED WEFT KNITTED  
FABRICS FOR WEARABLE APPLICATIONS**

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INDIAN INSTITUTE OF TECHNOLOGY DELHI  
MAY 2025**

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by

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Submitted

*in fulfilment of the requirements of the degree of Doctor of Philosophy*

to the



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**MAY 2025**

*Dedicated to my parents, Smt. Keshari Devi and Shri  
Lalji Maurya, whose love and blessings have been the  
foundation of my achievements.*

## CERTIFICATE

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This is to certify that the thesis entitled “**Electrothermal Characterization of Conductive Yarn-Integrated Weft Knitted Fabrics for Wearable Applications**”, submitted by **Mr. Sandeep Kumar Maurya** to the Indian Institute of Technology, Delhi, for the award of the degree of **Doctor of Philosophy** in the Department of Textile and Fibre Engineering, is a record of bonafide research work carried out by him. Mr. Sandeep Kumar Maurya diligently pursued his research work under our guidance and supervision and has fulfilled the requirements for the submission of the thesis, which, to our knowledge, aligns with the requisite standards for a PhD degree from this institute.

The results contained in the 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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**(Sandeep Kumar Maurya)**

## ABSTRACT

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E-textiles for wearable applications utilize textile structures, including knitting, weaving, and nonwoven fabrics, due to their excellent flexibility, breathability, and compatibility with the human body. Knitted-based wearable heaters, known for their flexibility and comfort, are gaining popularity as an innovative approach in thermotherapy applications. However, existing literature on textile-based wearable heaters has primarily focused on surface coatings of conductive materials, which often compromise the comfort and stretchability of the fabric, highlighting the need for more integrated and user-friendly approaches in the design and development of textile-based wearable heating solutions. In prior literature, conductive yarn integrated heaters are constructed using parallel configurations and rely on simple knitting structures such as single jersey, rib, and interlock to optimize the performance of heating fabrics. Furthermore, the literature lacks detailed characterization of conductive yarns specifically for heating applications. To address these limitations, the present research focuses on the comprehensive electrothermal characterization of conductive yarn-integrated knitted-based heaters for wearable applications.

In this study, the electrothermal and mechanical properties of stainless steel (SS) and silver-coated (SC) yarns were analyzed to evaluate their long-term durability and feasibility for use in knitted-based heating textiles. The yarn was prepared separately using the commercially available silver-coated nylon and stainless-steel filament on the two-for-one (TFO) machine. SC yarn offers superior heating performance over SS yarn due to its low resistance, but its long-term durability, washability, and thermal stability are lower than SS yarn. The SS yarn is thermally stable up to 70 °C with minimal resistance change. However, the resistance of SC yarn increased by 81.12%, and

the average temperature was reduced by 23.23% due to the oxidation of silver in an open environment after exposure for 50 days. The localized heating pad was designed using SC and SS cabled yarn. The temperature of the SC-based pad was 37.5 °C, while the temperature of the SS-based pad was 34.3 °C at a 9 V DC power supply.

Further, a simple rib knitting structure was used to fabricate the heating pad using stainless steel yarn and cotton yarn on the V-bed knitting machine with 14-gauge needles arrangement. The effectiveness of a parallel-based heating fabric was examined, utilizing three varied electrodes: copper (Cu), silver (Ag), and 85% Cu-15% Ni-coated woven fabrics. The Cu–Ni-coated fabric electrode, with its low surface resistivity of 0.061  $\Omega$ /square, is more suitable for parallel heating pad designs due to its superior charge-transfer efficiency. The parallel (P-CNKF-parallel with copper and nickel-coated electrode as the bus bar) and series-based heating pad could be heated up to 47 and 26 °C, respectively, at 9 V DC power source in the standard environment (20 °C and 65% RH) condition. Various insulating layers were placed over the parallel-based heating pad (P-CNKF), producing samples such as S1 (air-heating textile-air), S2 (lining-heating textile-lining), S3 (lining-fleece-heating textile-fleece), and S4 (lining-terry-heating textile-terry). The findings showed that samples S2, S3, and S4 demonstrated surface temperatures that were 17, 33, and 27% higher, respectively, compared to a heating pad without insulation. The findings suggest that using fleece-knitted insulation layers can boost the performance of heating pads, enabling their use in thermotherapy for joint and muscle pain, with reduced power consumption. However, A surface temperature of 28 °C can be maintained using a series-based heating pad with just 3 W of power, while a parallel-based heating textile requires 5 W. This demonstrates that the series-based heating textile is more efficient, requiring less power for the same temperature maintenance.

To optimize the performance of the series-based heater, modifications were implemented in the active region by adjusting various knitting structural parameters such as knit, float, and tuck. Four distinct knit-based heating pad designs were developed: 3R (three courses of knit), 3T (three courses of tuck), 3F (three courses of float), and FTF (first course float, second course tuck, and third course float). In comparison to the 3R structure, the surface temperature of the 3F and FTF knitted heating pads increased by 38.2 and 23%, respectively. The 3F knitted structure also exhibited the least temperature change due to float in the structure, which is 10.60 at a 60% extension level. The effect of relative humidity levels of 20, 40, 60, and 80% and surrounding temperatures of 20, 30, 40, and 50 °C with and without airflow on the efficiency of the 3F heating pad is investigated. No significant difference was found during the analysis of the surface temperature at various relative humidities. However, high surrounding temperature has a significant effect on the heating pad due to its diminished ability to transfer heat to its surroundings.

Additionally, the study examined the durability and comfort characteristics of knitted heating textiles, focusing on their long-term performance and practical usability in real-world conditions. The 3F sample exhibited the highest thermal resistance, air permeability, and water vapor permeability due to its structural characteristics. Flexural rigidity was lower in the course direction compared to the wale direction, providing greater flexibility and easier bending in the course direction of heating textiles. Moreover, after six washing cycles, surface temperature reductions of 10.31% (3R), 12.21% (3 T), 8.85% (3F), and 9.12% (FTF) were recorded. Bending cycles, perspiration, and detergent exposure showed no notable effects. However, in the 3 T structure, loosely bound fibers resulted in significant fiber breakage, leading to an 8.92% temperature change

following 5000 abrasion cycles. This research provides valuable insights into the characterization, optimization, and development of knitted heating textiles, highlighting their durability, comfort properties, and practical applicability.

## सार

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ई-टेक्सटाइल्स पहनने योग्य अनुप्रयोगों के लिए बुनाई और नॉनवोवन कपड़ों जैसी टेक्सटाइल संरचनाओं का उपयोग करते हैं, क्योंकि ये उत्कृष्ट लचीलापन, श्वसन की क्षमता और मानव शरीर के साथ अनुकूलता प्रदान करते हैं। बुनाई आधारित पहनने योग्य हीटर, जो अपने लचीलेपन और आराम के लिए जाने जाते हैं, थर्मोथेरेपी अनुप्रयोगों में एक नवाचारपूर्ण दृष्टिकोण के रूप में लोकप्रियता प्राप्त कर रहे हैं। हालांकि, ई-टेक्सटाइल हीटरों पर उपलब्ध साहित्य मुख्य रूप से प्रवाहकीय पदार्थों की सतही कोटिंग पर केंद्रित रहा है, जो अक्सर कपड़े के आराम और लचीलापन से समझौता करते हैं। यह इस क्षेत्र में अधिक एकीकृत और उपयोगकर्ता-अनुकूल डिज़ाइनों की आवश्यकता को दर्शाता है। पूर्व के शोधों में प्रवाहकीय यार्न से बने हीटरों को समानांतर विन्यास में विकसित किया गया है, जो सरल बुनाई संरचनाओं जैसे कि सिंगल जर्सी, रिब और इंटरलॉक पर आधारित होते हैं। इसके अतिरिक्त, प्रवाहकीय यार्न की विशेष रूप से हीटिंग अनुप्रयोगों के लिए विस्तृत विश्लेषण की कमी है। इन सीमाओं को दूर करने के लिए वर्तमान अनुसंधान प्रवाहकीय यार्न-समाकलित बुने हुए हीटरों की विद्युत-तापीय विशेषताओं के व्यापक विश्लेषण पर केंद्रित है।

इस अध्ययन में स्टेनलेस स्टील और सिल्वर-कोटेड यार्न की विद्युत-तापीय और यांत्रिक विशेषताओं का विश्लेषण किया गया, ताकि बुने हुए हीटिंग वस्त्रों में दीर्घकालिक स्थायित्व और उपयुक्तता का मूल्यांकन किया जा सके। धागे को टू-फॉर-वन (टीएफओ) मशीन पर व्यावसायिक रूप से उपलब्ध सिल्वर-कोटेड नायलॉन और स्टेनलेस स्टील फिलामेंट का उपयोग करके अलग से तैयार किया। कम प्रतिरोध के कारण सिल्वर कोटेड यार्न बेहतर हीटिंग प्रदर्शन प्रदान करता है, लेकिन इसका दीर्घकालिक स्थायित्व, धोने की क्षमता और तापीय स्थिरता स्टेनलेस स्टील यार्न की तुलना में कम है। स्टेनलेस स्टील यार्न 70°C तक तापीय

रूप से स्थिर रहता है जबकि 50 दिनों के खुले वातावरण में संपर्क के बाद सिल्वर-कोटेड यार्न की प्रतिरोधता में 81.12% की वृद्धि और औसत तापमान में 23.23% की कमी देखी गई। सिल्वर और स्टेनलेस स्टील यार्न से बने स्थानीय हीटिंग पैड का डिज़ाइन किया गया। 9V डीसी पावर सप्लाई पर सिल्वर-कोटेड आधारित पैड का तापमान 37.5°C और स्टेनलेस स्टील आधारित पैड का तापमान 34.3°C दर्ज किया गया।

आगे, स्टेनलेस स्टील और कॉटन यार्न का उपयोग करते हुए 14 गेज की वी-बेड बुनाई मशीन पर एक सरल रिब संरचना में हीटिंग पैड तैयार किया गया। समानांतर आधारित हीटिंग कपड़े की प्रभावशीलता का मूल्यांकन तीन प्रकार के इलेक्ट्रोड (कॉपर, सिल्वर और 85% कॉपर-15% निकल-लेपित बुने हुए कपड़े) के साथ किया गया। इनमें से, कॉपर-निकल लेपित इलेक्ट्रोड 0.061  $\Omega$ /वर्ग की कम सतही प्रतिरोधता के कारण बेहतर चार्ज ट्रांसफर दक्षता दर्शाता है। समानांतर (पी-सीएनकेफ) और श्रेणीक्रम हीटिंग पैड क्रमशः 9V डीसी पर 47°C और 26°C तक गरम हुए। इसके बाद विभिन्न इंसुलेटिंग लेयर के साथ नमूनों जैसे एस1 (एयर-हीटिंग टेक्सटाइल-एयर), एस2 (लाइनिंग-हीटिंग टेक्सटाइल-लाइनिंग), एस3 (लाइनिंग-फ्लीस-हीटिंग टेक्सटाइल-फ्लीस) और एस4 (लाइनिंग-टेरी-हीटिंग टेक्सटाइल-टेरी) को तैयार किया गया। इनके सतही तापमान क्रमशः 17%, 33% और 27% अधिक पाए गए। इससे सिद्ध होता है कि इंसुलेटिंग फ्लीस परतें हीटिंग प्रदर्शन में वृद्धि करती हैं और कम बिजली खपत के साथ थरेपी अनुप्रयोगों में उपयोगी हो सकती हैं। 3W पावर से 28°C तापमान बनाए रखने में श्रेणीक्रम हीटर अधिक कुशल पाया गया, जबकि समानांतर संरचना को 5W की आवश्यकता थी।

श्रेणीक्रम हीटर की कार्यक्षमता बढ़ाने हेतु बुनाई संरचना को संशोधित किया गया, जिसमें चार डिज़ाइन – 3 आर (तीन कोर्स बुनाई), 3 टी (तीन कोर्स टक), 3 एफ (तीन कोर्स फ्लोट), और एफ टी एफ (फ्लोट-टक-

फ्लोट) बनाए गए। 3 एफ और एफ टी एफ संरचनाओं ने 3R की तुलना में क्रमशः 38.2% और 23% अधिक सतही तापमान प्राप्त किया। 3 एफ संरचना ने खिंचाव के दौरान तापमान परिवर्तन में सबसे कम परिवर्तन (60% एक्सटेंशन पर 10.60°C) दिखाया। 3 एफ हीटिंग पैड पर विभिन्न आर्द्रता स्तर (20, 40, 60, 80%) और परिवेश तापमान (20, 30, 40, 50°C) के साथ वायु प्रवाह प्रभाव का अध्ययन किया गया। विभिन्न सापेक्ष आर्द्रताओं पर सतह के तापमान के विश्लेषण के दौरान कोई महत्वपूर्ण अंतर नहीं पाया गया। हालाँकि, उच्च परिवेश तापमान का हीटिंग पैड पर महत्वपूर्ण प्रभाव पड़ता है क्योंकि इसकी अपने परिवेश में गर्मी स्थानांतरित करने की क्षमता कम हो जाती है।

इसके अतिरिक्त, अध्ययन में बुने हुए हीटिंग टेक्सटाइल्स की स्थायित्व और आराम विशेषताओं की जांच की, जो वास्तविक दुनिया की स्थितियों में उनके दीर्घकालिक प्रदर्शन और व्यावहारिक उपयोगिता पर ध्यान केंद्रित करते हैं। 3एफ नमूने ने अपनी संरचनात्मक विशेषताओं के कारण उच्चतम तापीय प्रतिरोध, वायु पारगम्यता और जल वाष्प पारगम्यता का प्रदर्शन किया। वेल दिशा की तुलना में कोर्स दिशा में फ्लेक्सुरल कठोरता कम थी, जो हीटिंग टेक्सटाइल्स की दिशा में अधिक लचीलापन और आसान झुकने प्रदान करती है। इसके अलावा, छह धुलाई चक्रों के बाद, सतह के तापमान में 10.31% (3 आर ), 12.21% (3 टी), 8.85% (3 एफ), और 9.12% (एफ टी एफ ) की कमी दर्ज की गई। झुकने के चक्र, पसीना और डिटर्जेंट के संपर्क में आने से कोई उल्लेखनीय प्रभाव नहीं दिखा। हालांकि, 3 टी संरचना में, शिथिल रूप से बंधे हुए रेशों के कारण महत्वपूर्ण फाइबर टूटना हुआ, जिससे 5000 घर्षण चक्रों के बाद 8.92% तापमान परिवर्तन हुआ। यह शोध बुने हुए हीटिंग वस्त्रों के लक्षण-निर्धारण, अनुकूलन और विकास के बारे में बहुमूल्य जानकारी प्रदान करता है, तथा उनके स्थायित्व, आरामदायक गुणों और व्यावहारिक प्रयोज्यता पर प्रकाश डालता है।



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## **List of Abbreviations**

| <b>Terms</b>                      | <b>Abbreviations</b> |
|-----------------------------------|----------------------|
| Phase change materials            | PCMs                 |
| Stainless steel                   | SS                   |
| Silver coated                     | SC                   |
| Milliampere-hours                 | mAh                  |
| Two-dimensional                   | 2D                   |
| Poly(3,4-ethylenedioxythiophene)  | PEDOT                |
| Knitted heating fabrics           | KHFs                 |
| Polyvinylidene fluoride           | PVDF                 |
| Relative humidity                 | RH                   |
| Nanowires                         | NWs                  |
| Silver nanowires                  | AgNws                |
| Copper nanowires                  | CuNWs                |
| Twist per inch                    | TPI                  |
| Two-for-one                       | TFO                  |
| Direct current                    | DC                   |
| Energy dispersion X-ray           | EDX                  |
| Glass transition temperature      | T <sub>g</sub>       |
| Differential scanning calorimeter | DSC                  |
| Scanning electron microscope      | SEM                  |
| Internet of Things                | IOT                  |

|                                        |       |
|----------------------------------------|-------|
| Ultimate temperature                   | UT    |
| Polypyrrole                            | PPy   |
| Graphene oxide                         | GO    |
| Kawabata evaluation system for fabrics | KES-F |