

DESIGN AND INVESTIGATION OF THERMAL COMPRESSION SYSTEM

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**DEPARTMENT OF TEXTILE AND FIBRE
ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
APRIL 2025**

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**DESIGN AND INVESTIGATION OF THERMAL
COMPRESSION SYSTEM**

by

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**DEPARTMENT OF TEXTILE AND FIBRE
ENGINEERING**

Submitted

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

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

APRIL 2025

DEDICATED TO MY PARENTS

Mother (Smt. Geetha)

and

In loving memory of my

Father (Late Shri. Sankara Pillai. N)

CERTIFICATE

This is to certify that the thesis entitled “**Design and Investigation of Thermal Compression System**”, submitted by **Mr. Pramod S** 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. Pramod S 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 Ph.D. 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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ACKNOWLEDGEMENTS

I express my deep sense of gratitude to my supervisors, **Prof. Apurba Das, Prof. R. Alagirusamy, and Prof. Bipin Kumar**, from the **Department of Textile and Fibre Engineering, Indian Institute of Technology Delhi**, for their invaluable guidance, insightful suggestions, and constant encouragement throughout my research work. Their unwavering support and expertise have been instrumental in shaping this study.

I am also extremely grateful to my **SRC members** – **Prof. R. S. Rengasamy** (Chairman, SRC), **Prof. Abhijit Majumdar**, and **Prof. Sunil Jha** – for their valuable inputs and constructive feedback, which significantly contributed to the refinement of this research.

I extend my sincere appreciation to **Prof. Chandrashekher (IIT Delhi), Dr. P. C. Panchariya (Director, CSIR-CEERI, Pilani), and Dr. C. Anandharamakrishnan (Director, CSIR-NISIT)** for their insightful discussions and valuable support, which have greatly enriched my understanding and contributed to the progress of this research.

I would like to express my gratitude to my seniors **Dr. Shilpi Aggarwal, Dr. Rahul Gadkari, Dr. Hema Garg, and Dr. Rochak**, whose guidance, support, and encouragement have been invaluable throughout my research journey. Their mentorship has been a great source of motivation.

I would also like to sincerely thank **Sh. Praveen Roy**, Head of the Department, **Technology Translational and Innovation**, for his guidance and support. My appreciation extends to **Dr. Akhilesh Mishra**, Senior Scientist, **Department of Science and Technology (DST)**, for his valuable insights. I am deeply honored to acknowledge **Prof. Ashutosh Sharma**, Former

Secretary, DST, and **Prof. Abhay Karandikar**, Secretary, DST, for their encouragement and inspiration in fostering research and innovation.

I am thankful to the **Department of Textile and Fibre Engineering** for providing the necessary facilities and a conducive research environment. Special thanks to the **Head of Department** for their support and cooperation throughout my research journey.

I would like to extend my appreciation to the **technical and support team**, especially **Sh. Raj Kumar and Geethu Gopinath**, for their assistance in the execution of experiments, data collection, and technical support throughout my research. Their dedication and expertise have been invaluable in ensuring the smooth progress of this work.

A special note of gratitude to my **friends and colleagues**, whose encouragement, discussions, and companionship have made this journey more fulfilling. I also extend my appreciation to all those who have directly or indirectly contributed to this work.

Finally, I am deeply indebted to my **family** for their unconditional love, patience, and support. Their belief in me has been my greatest motivation throughout this endeavor.

(Pramod S)

Abstract

Thermocompression is a therapeutic technique that combines heat and compression to treat various medical conditions. It involves applying controlled heat to a specific body area while simultaneously exerting pressure through a compression mechanism. This method is particularly effective in reducing pain, inflammation, and swelling, and is often used to support the healing process in conditions such as sports injuries, chronic pain disorders, and post-surgical recovery. The heat helps to increase blood flow and relax muscles, while compression helps to reduce swelling and stabilize the affected area, thereby enhancing the overall therapeutic effect. Thermocompression therapy plays a critical role in the management of chronic pain, sports injuries, and post-surgical recovery, with conditions such as osteoarthritis and muscle strains benefiting significantly from the application of heat and compression. While effective, traditional thermotherapy devices, such as heat packs and wraps, are often bulky and rigid, limiting their usability and comfort and reducing patient compliance. These devices can also not maintain consistent therapeutic pressure over time, especially under varying environmental and dynamic conditions. Henceforth, the present research aims to integrate smart textiles and flexible electronics into a wearable thermo-compression system designed to overcome these limitations.

This study explores the design of heating fabrics using copper yarns with single, two-ply, and three-ply structures inserted at various intervals. The temperature distribution of the bare conductive yarn after inserting it into knitted fabric was analyzed. Further, the number of courses and plies of conductive copper yarn in the knitted fabric samples varied, and a significant influence on temperature distribution was shown. Results show that optimal yarn spacing, especially at 4

mm, enhances uniform heat distribution across the fabric. The three-ply yarn, inserted every two courses, reached the highest temperature of 99 °C at 4V, with rapid heating and consistent temperature stabilization. These fabrics demonstrate potential for thermal therapy applications, offering adjustable temperature control and effective heat distribution. Furthermore, a customizable thermo-compression device was developed to simulate dynamic conditions, sweating and temperature to study the interaction between thermal properties and compression effects in bandage interface pressure for wearables in real-life situations.

To realize the miniaturization of bulky thermal compression devices, flexible fabric heater and pressure sensors were developed. A screen-printed fabric heater was developed using silver-carbon composite ink on a polyester substrate in a meander configuration, which ensures flexibility, durability, and uniform heat distribution. The heater achieved temperatures of approximately 35 °C at 3V, 55 °C at 5V, and reached a maximum of around 85 °C at 7V. The heater reached 85% of its equilibrium temperature within the first 60 seconds of voltage application, indicating a quick thermal response that is beneficial for immediate heat therapy.

A flexible pressure sensor designed using a capacitive sensing technology with double-layered micro structured dielectric materials. The dielectric layers were made from an elastomeric silicone-based material, chosen for its flexibility, durability, and sensitivity to pressure changes. This material enables the sensor to conform to body contours comfortably while maintaining precise pressure measurements. The sensor showed high sensitivity across a 0–60 mmHg range, ideal for therapeutic compression monitoring. It demonstrated a quick response time of less than 1 second

with ± 1 mmHg accuracy and stability of 1000 bending cycles facilitating real-time adjustments. The findings of this research contribute to the development of lightweight, flexible, and efficient heating textiles with applications in wearable compression therapeutic devices, significantly advancing the field of smart textiles in healthcare and wellness.

सार

थर्मोकम्प्रेशन एक चिकित्सीय तकनीक है जो विभिन्न चिकित्सीय स्थितियों के इलाज के लिए गर्मी और संपीड़न को जोड़ती है। इसमें एक संपीड़न तंत्र के माध्यम से दबाव डालते हुए शरीर के एक विशिष्ट क्षेत्र पर नियंत्रित गर्मी लागू करना शामिल है। यह विधि विशेष रूप से दर्द, सूजन और सूजन को कम करने में प्रभावी है, और अक्सर इसका उपयोग खेल चोटों, पुराने दर्द विकारों और शल्य चिकित्सा के बाद की वसूली जैसी स्थितियों में उपचार प्रक्रिया का समर्थन करने के लिए किया जाता है। गर्मी रक्त प्रवाह को बढ़ाने और मांसपेशियों को आराम देने में मदद करती है, जबकि संपीड़न सूजन को कम करने और प्रभावित क्षेत्र को स्थिर करने में मदद करता है, जिससे समग्र चिकित्सीय प्रभाव बढ़ता है। थर्मोकम्प्रेशन थेरेपी पुराने दर्द, खेल की चोटों और सर्जरी के बाद की रिकवरी के प्रबंधन में महत्वपूर्ण भूमिका निभाती है, ऑस्टियोआर्थराइटिस और मांसपेशियों में खिंचाव जैसी स्थितियों में गर्मी और संपीड़न के अनुप्रयोग से काफी लाभ होता है। प्रभावी होते हुए भी, पारंपरिक थर्मोथेरेपी उपकरण, जैसे हीट पैक और रैप्स, अक्सर भारी और कठोर होते हैं, जिससे उनकी उपयोगिता और आराम सीमित हो जाता है और रोगी के अनुपालन में कमी आती है। ये उपकरण समय के साथ लगातार चिकित्सीय दबाव बनाए नहीं रख सकते हैं, खासकर अलग-अलग पर्यावरणीय और गतिशील परिस्थितियों में। इसके बाद, वर्तमान शोध का उद्देश्य इन सीमाओं को दूर करने के लिए डिज़ाइन किए गए पहनने योग्य थर्मो-संपीड़न प्रणाली में स्मार्ट टेक्स्टाइल और लचीले इलेक्ट्रॉनिक्स को एकीकृत करना है।

यह अध्ययन विभिन्न अंतरालों पर डाले गए एकल, दो-प्लेई और तीन-प्लेई संरचनाओं के साथ तांबे के धागों का उपयोग करके हीटिंग कपड़ों के डिज़ाइन की पड़ताल करता है। बुने हुए कपड़े में डालने के बाद नंगे प्रवाहकीय धागे के तापमान वितरण का विश्लेषण किया गया। इसके अलावा, बुने हुए कपड़े के नमूनों में प्रवाहकीय तांबे के धागे की संख्या और परतों की संख्या भिन्न थी, और तापमान वितरण पर एक महत्वपूर्ण प्रभाव दिखाया गया था। नतीजे बताते हैं कि इष्टतम यार्न अंतर, विशेष रूप से 4 मिमी, पूरे कपड़े में समान गर्मी वितरण को बढ़ाता है। तीन-प्लेई यार्न, हर दो कोर्स में डाला गया, तेजी से हीटिंग और लगातार तापमान स्थिरीकरण

के साथ, 4V पर 99 डिग्री सेल्सियस के उच्चतम तापमान तक पहुंच गया। ये कपड़े थर्मल थेरेपी अनुप्रयोगों के लिए क्षमता प्रदर्शित करते हैं, समायोज्य तापमान नियंत्रण और प्रभावी गर्मी वितरण की पेशकश करते हैं। इसके अलावा, वास्तविक जीवन की स्थितियों में पहनने योग्य वस्तुओं के लिए बैट्रेज इंटरफ़ेस दबाव में थर्मल गुणों और संपीड़न प्रभावों के बीच बातचीत का अध्ययन करने के लिए गतिशील स्थितियों, पसीने और तापमान का अनुकरण करने के लिए एक अनुकूलन योग्य थर्मो-संपीड़न उपकरण विकसित किया गया था।

भारी थर्मल संपीड़न उपकरणों के लघुकरण को साकार करने के लिए, लचीले फैब्रिक हीटर और दबाव सेंसर विकसित किए गए थे। मेन्डर कॉन्फ़िगरेशन में पॉलिएस्टर सबस्ट्रेट पर सिल्वर-कार्बन मिश्रित स्याही का उपयोग करके एक स्क्रीन-प्रिंटेड फैब्रिक हीटर विकसित किया गया था, जो लचीलापन, स्थायित्व और समान गर्मी वितरण सुनिश्चित करता है। हीटर ने 3V पर लगभग 35°C, 5V पर 55°C और 7V पर लगभग 85°C का अधिकतम तापमान प्राप्त किया। वोल्टेज अनुप्रयोग के पहले 60 सेकंड के भीतर हीटर अपने संतुलन तापमान के 85% तक पहुंच गया, जो त्वरित थर्मल प्रतिक्रिया का संकेत देता है जो तत्काल हीट थेरेपी के लिए फायदेमंद है।

एक लचीला दबाव सेंसर जिसे डबल-लेयर सूक्ष्म संरचित ढांकता हुआ सामग्रियों के साथ कैपेसिटिव सेंसिंग तकनीक का उपयोग करके डिज़ाइन किया गया है। ढांकता हुआ परतें इलास्टोमेरिक सिलिकॉन-आधारित सामग्री से बनाई गई थीं, जिसे इसके लचीलेपन, स्थायित्व और दबाव परिवर्तनों के प्रति संवेदनशीलता के लिए चुना गया था। यह सामग्री सटीक दबाव माप बनाए रखते हुए सेंसर को शरीर के आकार के अनुरूप आराम से रहने में सक्षम बनाती है। सेंसर ने 0-60 एमएमएचजी रेंज में उच्च संवेदनशीलता दिखाई, जो चिकित्सीय संपीड़न निगरानी के लिए आदर्श है। इसने वास्तविक समय समायोजन की सुविधा प्रदान करते हुए ± 1 mmHg सटीकता और 1000 झुकने वाले चक्रों की स्थिरता के साथ 1 सेकंड से भी कम समय का त्वरित प्रतिक्रिया समय प्रदर्शित किया।

इस शोध के निष्कर्ष पहनने योग्य संपीडन चिकित्सीय उपकरणों में अनुप्रयोगों के साथ हल्के, लचीले और कुशल हीटिंग वस्त्रों के विकास में योगदान करते हैं, जो स्वास्थ्य देखभाल और कल्याण में स्मार्ट वस्त्रों के क्षेत्र को महत्वपूर्ण रूप से आगे बढ़ाते हैं।

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List of Abbreviations

Terms	Abbreviations
Lensless fourier transform digital holography	LLFTDH
Phase change materials	PCM
Chronic venous insufficiency	CVI
Intermittent pneumatic compression	IPC
Randomized controlled trials	RCT
Local warming therapy	LWT
Digital holography interferometry	DHI
Multiwalled carbon nanotube	MWCNT
Silver nanofibre	Ag NF
Silver fractal dendrites	Ag FDs
Polydimethylsiloxane	PDMS
Trichloro(1H,1H,2H,2H-perfluorooctyl) silane	PFOTS
Buffer oxide etchant	BOE
Indium oxide coated polyethylene terephthalate	IO-PET
Polyethylene terephthalate	PET