Contributions to the Study and Development of Innovative Textile Materials for Thermal Comfort and Performance

ABSTRACT

The habilitation thesis titled *"Contributions to the Study and Development of Innovative Textile Materials for Thermal Comfort and Performance"* presents a part of the scientific and professional activities and results of the candidate Elena Codău (Onofrei), published in journals and proceedings of scientific events following the attainment of the Doctorate in *Industrial Engineering*. The doctoral degree was awarded under diploma no. 1672/01.10.2003 for the *thesis "Theoretical and Experimental Contributions to the Study and Optimization of the Technological Process for Producing Cotton-Type Yarns"*, supervised by Prof. Dr. Eng. Constantin Preda.

This work certifies the candidate's ability to lead scientific research in the field of Industrial Engineering, specifically in the direction of developing innovative, smart textile products using advanced technologies. The goal is to create multifunctional, high-value-added products that contribute to improving the quality and safety of life for users.

The habilitation thesis is structured into two parts. The first part presents the main scientific and academic achievements of the candidate, Elena Codău (Onofrei), throughout her university career at the "Gheorghe Asachi" Technical University of Iași, Faculty of Industrial Design and Business Management, as well as her research activities conducted at the University of Minho in Portugal, the Catholic University of Lille in France, and ENSAIT-Roubaix, France. The second part outlines the candidate's professional and academic objectives, along with the main directions of scientific research, emphasizing her ability to organize and manage teaching and research activities.

The chapters in *the first part* of the habilitation thesis outline the following research directions:

- Development and design of smart textile materials for monitoring heat and mass transfer in protective equipment for firefighters, as well as in medical, sports, and geotextile applications.
- Modeling and simulation of heat and moisture transfer through textile materials.
- Development of functionalized textile structures for sports applications, utilizing phase-change materials.

Chapter I - Heat transfer through textile materials

This chapter explores the mechanisms and analytical methods related to heat transfer in textile materials, focusing on thermal comfort, thermal properties, and the use of electronic textiles for thermal flux monitoring. Experimental methods for analysing the thermal properties of textile materials are detailed, including:
- The use of heat flux sensors to measure thermal resistance.
- The application of heat flux sensors to determine the thermal convection coefficient.
- The assessment of optical properties of textiles that influence their interaction with thermal radiation.

The chapter also examines the integration of electronic technology into textile materials for thermal monitoring. Innovative, original methods for measuring heat flux through textiles equipped with integrated sensors are described.
The chapter highlights the importance of combining traditional knowledge about textile materials with new technologies to enhance comfort and material performance across various applications.

Chapter II - Modeling and simulation of heat transfer through textile materials

This chapter investigates the modeling of heat transfer in textile materials, addressing both experimental and numerical methods to understand and optimize their thermal behavior.
A review of the specialized literature is conducted, highlighting recent advances, trends, and challenges in the modeling of heat transfer through textile materials.
The chapter presents the author's own investigations, which include:
- Experimental simulation of the heat transfer process through single-layer and multi-layer textile materials.
- Numerical modeling of the thermal behavior of textile materials under routine thermal conditions. Techniques for numerical modeling of heat transfer phenomena are detailed, both at the macroscopic and microscopic levels, exploring the interactions between the structural components of textiles and thermal flux.
This chapter provides an integrated perspective on modeling methods, emphasizing their applicability in enhancing the thermal properties of textile materials.

Chapter III – Moisture transfer through textile materials

This chapter emphasizes the interdependence between moisture transfer and the thermal performance of textile materials, providing valuable insights for optimizing their design and application.
A synthesis is presented on the significance of moisture transfer, highlighting recent advances in the field and challenges in characterizing textile materials from this perspective. International standards and specific parameters used to evaluate the capacity of textile materials to transfer water vapor are detailed.
The chapter discusses the effects of variations in air relative humidity on the thermal properties of textile materials, as well as the changes in thermal performance caused by the presence of moisture within the material.

Chapter IV – Modeling and simulation of simultaneous heat and moisture transfer through textile materials

This chapter explores modeling and numerical simulation methods to understand and analyse the simultaneous transfer of heat and moisture through textile materials, both at macroscopic and microscopic levels.
Fundamental concepts and theoretical approaches for describing the complex processes of heat and moisture transfer in textiles are presented, emphasizing the factors influencing these phenomena.
The author’s macroscopic simulations analyse the simultaneous transfer of heat and moisture at the material’s global structure, integrating practical usage conditions. Microscopic simulations investigate detailed interactions at the level of fibers and pores, providing an in-depth understanding of mass transfer phenomena at the microstructural scale.
This chapter offers a comprehensive approach, highlighting the importance of modeling and numerical simulation in optimizing the performance of textile materials for various applications.

Chapter V – Phase-change textile materials for ensuring thermal comfort

This chapter investigates the use of phase-change materials (PCMs) in textiles to enhance thermal comfort, analysing their properties and methods for characterizing and simulating their functionality.

An introduction to phase-change materials is provided, explaining their operating principles and applicability in textiles for regulating the wearer's temperature.

The chapter highlights the author's original contributions to evaluating the thermal performance of PCM-based textiles. The use of differential scanning calorimetry (DSC) for analyzing the thermal behavior of textile materials containing PCMs during the phase-change process is detailed, alongside the application of a thermal manikin to test thermal performance under realistic conditions. Additionally, a numerical simulation conducted by the author is presented, assessing the functional behavior of textiles with embedded PCMs and emphasizing their potential for optimization across various applications.

This chapter provides a comprehensive overview of the potential of PCM-based materials in textiles, contributing to advancements in the field of thermal comfort.

The second part of the habilitation thesis outlines the strategic plan for the author's scientific and professional career development, focusing on key objectives and primary research directions for the future.

The research directions align with European and global efforts to create innovative, high-quality functional products - such as protective, medical, and other specialized textiles - that ensure optimal comfort parameters for the wearer.

A promising research avenue is the development of thermoelectric textile materials, aimed at providing sustainable and innovative energy solutions. The author has already initiated studies in this direction, resulting in the publication of scientific papers.

This chapter presents research dedicated to the development of polymer-based composite textile materials designed to create *flexible and wearable thermoelectric devices.* These devices target the conversion of thermal energy into electrical energy, with applications in renewable energy, healthcare, sports, and biological signal monitoring.

Key highlights include:

- The use of conductive polymers, such as polyaniline, polypyrrole, and PEDOT: PSS, with improved properties achieved through doping, structural modifications, and the integration of nanomaterials (e.g., carbon nanotubes, graphene).
- The identification of electrospinning as a promising technique for producing thermoelectric nanofibers with customized properties. Functionalized carbon nanotubes enhance electrical conductivity, and the resulting hybrid structures are characterized using electron microscopy and impedance spectroscopy.
- Evaluation of thermoelectric properties using Seebeck coefficient, electrical conductivity, and power factor measurements.

The developed textile materials have the potential to be integrated into portable devices, self-powered sensors, and smart textiles. Emphasis is placed on biocompatibility, durability in various environmental conditions, and the sustainability of manufacturing processes.