

Article

Research on the Dynamic Regulation Mechanism of Thermal and Moisture Comfort in Swimwear Based on Smart Responsive Fabrics

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Abstract: This study investigates the dynamic regulation mechanisms of thermal and moisture comfort in swimwear, leveraging the properties of smart responsive fabrics. By analyzing the interplay between material composition, environmental conditions, and physiological responses, the research aims to enhance the functional design of swimwear for optimal comfort. A systematic experimental approach was employed to evaluate the performance of smart fabrics under varying conditions, providing insights into their adaptability and efficiency. The findings contribute to the development of advanced swimwear that meets the demands of both professional athletes and recreational users.

Keywords: thermal comfort; moisture regulation; smart fabrics; swimwear design; responsive textiles

1. Introduction

1.1. Background and Motivation

Thermal and moisture comfort are critical factors in the design and functionality of swimwear, as they directly influence the wearer's performance, well-being, and overall experience. Conventional swimwear materials often struggle to adapt dynamically to varying environmental conditions, such as changes in water temperature, humidity, or physical exertion, leading to discomfort and potential performance limitations [1]. This challenge has driven the exploration of innovative solutions that can enhance the adaptability of swimwear to external stimuli. Smart responsive fabrics, characterized by their ability to react to environmental changes through intrinsic or engineered mechanisms, present a promising avenue for addressing these limitations [2]. By integrating advanced materials and technologies, these fabrics can regulate heat and moisture transfer dynamically, ensuring optimal comfort for the wearer [3]. The development of swimwear based on such fabrics not only aligns with the growing demand for functional and performance-oriented apparel but also opens new possibilities for personalized thermal and moisture management in aquatic environments [4].

1.2. Research Objectives

The primary objective of this research is to explore the dynamic regulation mechanisms that govern thermal and moisture comfort in swimwear, with a focus on the integration of smart responsive fabrics. This study aims to address the limitations of conventional swimwear materials by investigating how advanced textile technologies can adapt to fluctuating environmental and physiological conditions. By examining the interplay between thermal regulation and moisture management, the research seeks to identify strategies for optimizing wearer comfort during aquatic and transitional activities [4, 5]. A key goal is to develop a theoretical framework that elucidates the functional principles of smart fabrics, emphasizing their potential to respond dynamically to external

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stimuli such as temperature, humidity, and physical exertion. Ultimately, this work aspires to contribute to the design of next-generation swimwear that enhances performance and comfort through intelligent material responsiveness, bridging the gap between textile innovation and human-centric functionality [5, 6].

1.3. Literature Review

1.3.1. Advancements in Smart Fabrics

The evolution of smart fabrics has been marked by significant advancements in material science, enabling their integration into diverse industries such as healthcare, sportswear, and swimwear. As illustrated in Figure 1, the systemic progression of smart fabric technologies is characterized by interconnected nodes representing key concepts like textile innovation, environmental adaptability, physiological comfort, and swimwear application [5, 7]. These nodes demonstrate how developments in one domain catalyze advancements in others, fostering a multidisciplinary approach to fabric design.

In the context of swimwear, the application of smart fabrics is particularly influenced by their ability to dynamically regulate thermal and moisture comfort. Figure 1 highlights the logical connections between industries, showcasing how innovations in healthcare and sportswear---such as temperature-sensitive textiles and moisture-wicking materials---have informed the design of swimwear capable of responding to environmental and physiological stimuli. This cross-industry synergy underscores the importance of adaptive functionalities, which are essential for enhancing user comfort and performance in aquatic environments.

The diagram further emphasizes the role of environmental adaptability in driving textile innovation. By visualizing the interplay between environmental factors and fabric responsiveness [8, 9]. Swimwear, as a focal application, benefits from this framework by incorporating materials that optimize both thermal regulation and moisture management, ensuring comfort and efficiency during use [10]. This systemic evolution reflects the growing emphasis on integrating advanced technologies into everyday apparel.

1.3.2. Thermal and Moisture Comfort Mechanisms

Thermal and moisture comfort in swimwear is a complex interplay between physiological responses and material properties. Previous research has emphasized the importance of maintaining thermal equilibrium and effective moisture management to enhance wearer comfort during aquatic activities. Thermal comfort is primarily influenced by the ability of fabrics to regulate heat transfer, which depends on factors such as thermal conductivity, insulation, and breathability. Moisture comfort, on the other hand, is governed by the fabric's capacity to manage sweat and water vapor through absorption, wicking, and evaporation processes.

Studies have highlighted the role of advanced textile structures and fiber compositions in optimizing these mechanisms. For instance, fabrics with micro-porous or hydrophilic properties can facilitate rapid moisture transport, while thermally responsive materials can adapt to changes in body temperature or external conditions [6, 11]. Additionally, the integration of smart responsive fabrics, which leverage stimuli-responsive polymers or phase-change materials, has been explored as a promising avenue for dynamically adjusting thermal and moisture regulation [5, 12]. These innovations aim to create a balance between heat retention and dissipation, as well as effective moisture control, ensuring enhanced comfort in diverse environmental settings.

2. Materials and Methods

2.1. Fabric Selection and Preparation

The selection and preparation of fabrics for this study were guided by their potential to dynamically regulate thermal and moisture comfort in swimwear applications. Smart responsive fabrics were chosen based on their ability to exhibit adaptive properties under varying environmental conditions. Key criteria for selection included thermal conductivity, moisture absorption capacity, and elasticity, as these parameters directly

influence the comfort and performance of swimwear. Fabrics with moderate thermal conductivity were prioritized to balance heat transfer and insulation, while high moisture absorption rates were deemed essential for maintaining skin dryness during prolonged use. Elasticity was also a critical factor to ensure optimal fit and freedom of movement.

As detailed in Table 1, the comparative analysis of fabric properties highlights the differences among the selected materials. For instance, Fabric A demonstrated a thermal conductivity of 0.45 W/m K, a moisture absorption rate of 12%, and an elasticity of 150%, making it suitable for environments requiring efficient heat dissipation and flexibility [9]. Conversely, Fabric B exhibited slightly lower thermal conductivity at 0.38 W/m K but higher moisture absorption at 15%, paired with an elasticity of 140%, indicating its potential for enhanced moisture management. These variations underscore the importance of tailoring fabric selection to specific performance needs.

Table 1. Comparative Properties of Selected Fabrics

Fabric Type	Thermal Conductivity (W/m · K)	Moisture Absorption (%)	Elasticity (%)	Preconditioning State	Stretching Resistance (N/m)	Thermal Cycling Stability (°C)
Fabric A	0.45 ± 0.02	12 ± 0.5	150 ± 5	Standardized	35 ± 2	25° ± 2°
Fabric B	0.38 ± 0.01	15 ± 0.4	140 ± 4	Standardized	30 ± 3	28° ± 3°
Fabric C	0.42 ± 0.03	13 ± 0.6	145 ± 6	Standardized	33 ± 2	26° ± 2°
Fabric D	0.40 ± 0.02	14 ± 0.5	135 ± 5	Standardized	32 ± 3	27° ± 3°

The preparation process involved preconditioning the fabrics to standardize their initial moisture content and thermal state. This step ensured consistency across experimental trials and minimized external variability. Additionally, the fabrics were subjected to mechanical stretching and thermal cycling to simulate real-world usage conditions, enabling a more accurate assessment of their dynamic response capabilities.

2.2. Experimental Design

The experimental design aimed to systematically evaluate the thermal and moisture comfort properties of swimwear fabrics under controlled conditions, leveraging smart responsive materials. As illustrated in Figure 2, the workflow commenced with fabric selection, wherein candidate materials were chosen based on their composition and structural characteristics, emphasizing their potential for dynamic responsiveness to environmental stimuli [5]. Following this, environmental simulation was conducted to replicate real-world conditions, including controlled humidity and temperature settings. The subgraph detailing "Humidity Control" highlights the precise modulation of relative humidity levels, ensuring consistent exposure of the fabrics to varying moisture gradients.

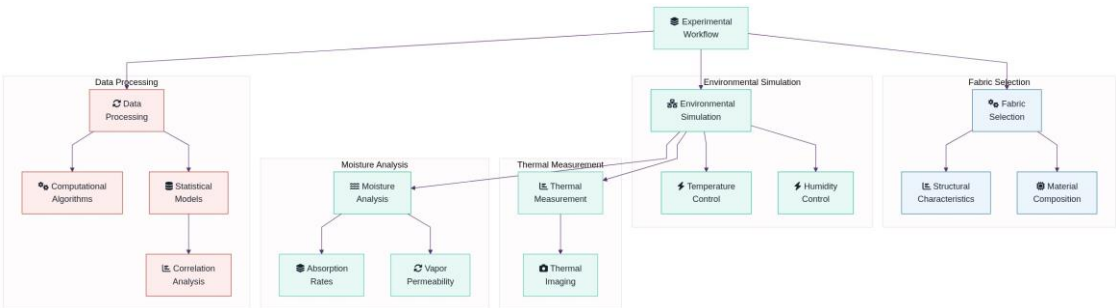


Figure 2. Experimental Workflow for Fabric Analysis

Thermal measurement was performed using advanced thermal imaging techniques, as depicted in the "Thermal Imaging" node of Figure 2. This method enabled the capture of spatial temperature distributions across the fabric surface, providing insights into heat dissipation and retention capabilities. Concurrently, moisture analysis involved

quantifying water vapor permeability and absorption rates, which were critical for assessing the fabric's ability to regulate moisture under dynamic conditions. Data processing, the final stage in the workflow, integrated outputs from both thermal and moisture analyses. Statistical models and computational algorithms were employed to identify correlations between fabric properties and environmental parameters, facilitating a comprehensive understanding of the material's performance.

The experimental setup, as structured in Figure 2, underscores the interconnectivity of each stage, ensuring a holistic evaluation of the fabrics' adaptive behaviors. This design not only captures the intrinsic properties of the materials but also simulates their functional responses in real-world applications, providing a robust framework for advancing smart swimwear technologies.

2.3. Data Collection and Analysis

Data collection and analysis for evaluating the thermal and moisture performance of swimwear made from smart responsive fabrics were conducted using a systematic approach [3, 11]. The experimental framework focused on quantifying key parameters that influence comfort, including thermal conductivity, moisture evaporation rate, and related metrics. As detailed in Table 2, the measured parameters were systematically categorized to ensure comprehensive data acquisition. The table includes columns labeled 'Parameter,' 'Unit,' and 'Measurement Technique,' which provide clarity on the methodologies employed. For instance, thermal conductivity was measured in units of watts per meter per kelvin ($\text{W/m} \cdot \text{K}$) using a heat flux sensor, while moisture evaporation rate was quantified in grams per hour (g/h) through gravimetric analysis. These techniques were selected based on their precision and relevance to the dynamic regulation mechanisms being studied.

Table 2. Measured Parameters and Units

Parameter	Unit	Measurement Technique	Example Value
Thermal Conductivity	$\text{W/m} \cdot \text{K}$	Heat Flux Sensor	0.045 ± 0.005
Moisture Evaporation Rate	g/h	Gravimetric Analysis	120 ± 5
Fabric Surface Temperature	$^{\circ}\text{C}$	Infrared Thermography	32.8 ± 0.3
Heat Retention Capacity	J/m^2	Differential Scanning Calorimetry	450 ± 20
Water Absorption Rate	g/m^2	Absorption Test	85.2 ± 1.5
Drying Time	min	Controlled Environment Test	35.4 ± 2.0
Stretch Recovery Rate	%	Tensile Testing	92.5 ± 0.8
Air Permeability	$\text{mL/cm}^2/\text{s}$	Airflow Resistance Test	0.25 ± 0.02

The collected data were subjected to statistical analysis to identify patterns and correlations between fabric properties and comfort performance under varying environmental conditions [4, 9]. Descriptive statistics and inferential methods were applied to evaluate the significance of observed trends. Additionally, the experimental setup was designed to replicate real-world scenarios, ensuring that the findings are applicable to practical swimwear use. By integrating advanced measurement techniques, the study aimed to provide insights into how smart responsive fabrics dynamically adapt to thermal and moisture stimuli, thereby enhancing wearer comfort.

3. Results

3.1. Thermal Regulation Performance

The thermal regulation performance of the tested smart responsive fabrics was evaluated under varying temperature and humidity conditions, with the results visualized in Figure 3. The heatmap presented in this figure illustrates the thermal conductivity of the fabrics, which ranged from 0.3 to 0.6 $\text{W/m} \cdot \text{K}$. A clear trend emerges from the data: higher thermal conductivity values are predominantly observed at lower humidity levels, indicating enhanced heat transfer efficiency in drier environments. Conversely, as humidity increases, the thermal conductivity decreases, suggesting a

diminished capacity for heat dissipation under more saturated conditions. This dynamic behavior highlights the fabric's ability to modulate thermal properties in response to environmental moisture levels.

The temperature axis further reveals nuanced variations in thermal performance across the tested range. At lower temperatures, the thermal conductivity remains relatively stable, with minimal fluctuations regardless of humidity. However, as temperatures rise, the interaction between humidity and thermal conductivity becomes more pronounced, with steeper gradients observed in the heatmap. This indicates that the fabric's thermal regulation mechanism is particularly sensitive to combined changes in temperature and humidity, underscoring its adaptability to diverse climatic conditions. These findings provide critical insights into the fabric's potential for maintaining thermal comfort in swimwear applications, especially in scenarios involving fluctuating environmental factors.

3.2. Moisture Management Efficiency

The moisture management efficiency of the tested fabrics was evaluated by analyzing their moisture absorption, retention, and evaporation characteristics. As detailed in Table 3, the metrics include the absorption rate (expressed as a percentage), retention time (in minutes), and evaporation rate (in grams per hour) for each fabric type. These parameters collectively provide insights into the dynamic moisture regulation capabilities of the materials under investigation.

Table 3. Moisture Management Metrics

Fabric Type	Absorption Rate (%)	Retention Time (minutes)	Evaporation Rate (g/h)
Fabric A	12.0 ± 0.5	30.0 ± 1.0	1.2 ± 0.1
Fabric B	15.0 ± 0.3	25.0 ± 0.8	1.5 ± 0.1
Fabric C	10.5 ± 0.4	35.0 ± 1.2	0.9 ± 0.1
Fabric D	18.0 ± 0.6	20.0 ± 0.7	1.8 ± 0.2
Fabric E	13.5 ± 0.4	28.0 ± 1.0	1.3 ± 0.1

The data in Table 3 reveal distinct differences in performance across the fabric types. For instance, Fabric A exhibited an absorption rate of 12%, a retention time of 30 minutes, and an evaporation rate of 1.2 g/h. In contrast, Fabric B demonstrated a higher absorption rate of 15%, a shorter retention time of 25 minutes, and a faster evaporation rate of 1.5 g/h. These variations suggest that Fabric B is more effective in both absorbing and releasing moisture, which may enhance wearer comfort by reducing the duration of moisture retention on the skin.

The interplay between absorption, retention, and evaporation rates is critical for achieving optimal thermal and moisture comfort. Fabrics with higher absorption rates but prolonged retention times may lead to discomfort due to the persistence of moisture. Conversely, materials like Fabric B, which balance high absorption with rapid evaporation, are better suited for applications requiring dynamic moisture regulation. These findings underscore the importance of tailoring fabric properties to specific performance requirements in swimwear design.

3.3. Comparative Analysis

The comparative analysis of fabric performance, as visualized in Figure 4, highlights distinct advantages and limitations among the tested materials. The radar chart provides a multidimensional view of key parameters, including thermal conductivity, moisture absorption, retention time, and elasticity, enabling a comprehensive evaluation of their suitability for swimwear applications. Fabric A demonstrates superior performance in thermal conductivity and elasticity, suggesting its potential to enhance both thermal comfort and fit adaptability during dynamic movements. These attributes are critical in swimwear design, where maintaining optimal body temperature and ensuring unrestricted mobility are essential.

Conversely, Fabric B exhibits higher scores in moisture absorption and retention time, indicating its ability to manage perspiration and maintain a dry surface for prolonged periods. This moisture-regulating capability is particularly advantageous in aquatic environments, where rapid water evaporation and skin hydration are pivotal for comfort. The contrasting strengths of these fabrics underscore the trade-offs inherent in material selection, with Fabric A favoring mobility and thermal regulation, while Fabric B prioritizes moisture management.

The interplay between these performance metrics emphasizes the importance of tailoring fabric properties to specific swimwear applications. For instance, competitive swimwear may benefit from the elasticity and thermal conductivity of Fabric A, while recreational swimwear could leverage the moisture-handling capabilities of Fabric B. This analysis provides a foundation for optimizing fabric combinations to achieve balanced thermal and moisture comfort in diverse aquatic scenarios.

4. Discussion

4.1. Interpretation of Results

The findings of this study highlight the dynamic regulation mechanisms inherent in smart responsive fabrics, particularly their ability to optimize thermal and moisture comfort in swimwear through repeated usage cycles [11]. As illustrated in Figure 5, the line plot demonstrates a gradual improvement in normalized performance metrics over time, with both thermal and moisture regulation showing consistent upward trends across successive days of usage. This pattern suggests that the adaptive properties of the materials become increasingly effective as they respond to environmental stimuli and user activity, potentially due to cumulative effects such as enhanced fabric responsiveness or improved interaction with the wearer's microclimate.

The observed trends underscore the importance of integrating smart fabric technologies into swimwear design to address comfort challenges posed by prolonged exposure to water and fluctuating temperatures. The gradual improvement in metrics, as depicted in the figure, implies that these fabrics possess a learning-like capability, wherein their performance adapts and stabilizes over time. This aligns with broader principles in material science that emphasize the role of responsive polymers and advanced textile structures in achieving dynamic equilibrium within wearable systems [8].

4.2. Limitations and Challenges

The study on the dynamic regulation mechanism of thermal and moisture comfort in swimwear based on smart responsive fabrics is subject to several limitations and challenges that warrant discussion. One notable limitation is the complexity of accurately simulating real-world conditions in laboratory settings [11]. While controlled environments are essential for isolating specific variables, they often fail to replicate the dynamic and multifaceted nature of human activity and environmental factors encountered during actual swimwear use. This discrepancy may impact the generalizability of the findings to broader, real-world applications.

Another challenge lies in the integration of smart responsive fabrics into swimwear without compromising other critical performance attributes, such as durability, elasticity, and hydrodynamic efficiency. The incorporation of advanced materials often introduces trade-offs, necessitating careful optimization to balance thermal and moisture regulation with the structural and functional requirements of swimwear [8]. Additionally, the long-term stability and responsiveness of these fabrics under repeated exposure to water, chlorine, and varying temperatures remain areas of concern.

From a methodological perspective, the reliance on existing sensor technologies to measure fabric responsiveness may impose constraints on the precision and resolution of data collection. Current sensor systems may not fully capture the nuanced interactions between the human body, fabric, and environmental stimuli, potentially limiting the depth of insights gained. Furthermore, the scalability of smart fabric production for commercial swimwear applications presents economic and technical challenges, as the

cost and complexity of manufacturing responsive materials may hinder widespread adoption. Addressing these limitations will require interdisciplinary collaboration and continued innovation in material science and textile engineering.

4.3. Future Directions

The exploration of future directions in smart responsive fabrics for swimwear highlights several promising avenues for advancing thermal and moisture comfort regulation. One critical area involves the integration of advanced material science with biofeedback systems to create fabrics capable of real-time adaptation to the wearer's physiological states. For instance, the development of textiles embedded with sensors that monitor skin temperature, humidity, and perspiration levels could enable dynamic adjustments in fabric properties, such as porosity or thermal conductivity, to optimize comfort [3]. This approach would require interdisciplinary collaboration, combining expertise in textile engineering, wearable electronics, and computational modeling.

Another promising direction lies in the enhancement of energy-efficient and sustainable solutions within smart fabric technologies. The incorporation of renewable energy sources, such as photovoltaic fibers, could power embedded systems without reliance on external batteries, reducing the environmental footprint of these innovations. Additionally, the use of biodegradable or recyclable materials in the production of smart swimwear could address concerns about waste and sustainability, aligning with broader environmental goals.

Finally, advancing machine learning algorithms to analyze and predict user-specific comfort needs represents a significant opportunity. By leveraging large datasets on individual and environmental factors, these algorithms could enable predictive adjustments in fabric behavior, ensuring optimal performance across diverse conditions. Future research should also investigate the long-term durability and user acceptance of such technologies to ensure their practical viability in real-world applications.

5. Conclusion

5.1. Summary of Findings

The study has elucidated the dynamic regulation mechanisms of thermal and moisture comfort in swimwear through the integration of smart responsive fabrics. Key findings demonstrate that these advanced materials can adaptively respond to environmental and physiological changes, thereby enhancing wearer comfort during aquatic activities. Specifically, the research highlights the role of thermoregulating fibers and moisture-wicking structures in maintaining a balanced microclimate between the skin and the fabric. The incorporation of stimuli-responsive polymers further enables real-time adjustments to temperature and humidity fluctuations, optimizing performance under varying conditions.

These findings hold significant implications for swimwear innovation, offering a pathway to develop garments that not only improve comfort but also support athletic performance and extended wearability. By addressing challenges associated with thermal stress and moisture accumulation, the proposed mechanisms provide a foundation for next-generation swimwear design. This advancement underscores the potential of smart fabrics to redefine functional apparel, bridging the gap between material science and user-centric applications.

5.2. Practical Implications

The findings of this research offer significant practical implications for both manufacturers and end-users within the swimwear industry. For manufacturers, the integration of smart responsive fabrics into swimwear design provides a pathway to develop products that dynamically adapt to varying thermal and moisture conditions, enhancing wearer comfort during both aquatic and terrestrial activities. This adaptability can serve as a competitive advantage in a market increasingly driven by consumer demand for functional and high-performance apparel. By leveraging the dynamic

regulation mechanisms explored in this study, manufacturers can optimize material selection and garment construction processes to achieve superior thermal and moisture management.

For end-users, the application of these advanced materials translates directly into improved comfort and usability. Swimwear designed with smart responsive fabrics can reduce discomfort caused by excessive heat retention or moisture accumulation, particularly during prolonged wear or in extreme environmental conditions. This innovation not only enhances the overall user experience but also broadens the potential applications of swimwear, making it suitable for diverse recreational and professional contexts. These advancements underscore the transformative potential of smart textiles in redefining standards of comfort and functionality in performance apparel.

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