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Integrated Design of Flexible Temperature Sensor and Temperature Regulation Module and Its Adaptability Research in Smart Clothing

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ABSTRACT To address the coordination issue between temperature sensing and dynamic thermal management in smart clothing, this study investigates the seamless integration of fiber-based flexible sensors and textile-integrated temperature regulation modules. By embedding these components directly into intelligent fabric structures, the proposed design improves wearing comfort and environmental adaptability while supporting the development of wearable electromagnetic sensing and intelligent thermal management systems. Experimental results show that the flexible temperature sensor exhibits a Temperature Coefficient of Resistance (TCR) of -3.8%/°C, a response time of 0.35 s, and a temperature measurement accuracy of ±0.1°C within the range of 0–50°C. The temperature regulation module achieves precise control within the comfort range of 28–38°C, with a heating rate of 1.1°C/min and a heating uniformity error below 5%. After 500 bending cycles, the integrated system demonstrates performance attenuation below 8%, maintains good compatibility with knitted and woven fabrics, and preserves air permeability above 82%. Spectral analysis confirms that the sensor resistance–temperature response mechanism is insensitive to visible light, while the flexible encapsulation design provides sufficient expansion space for the PTC effect. The proposed integrated architecture offers reliable technical support for dynamic thermal management in smart clothing and provides valuable references for wearable electromagnetic sensing, intelligent physiological monitoring, and multifunctional electronic textile applications.

INDEX TERMS flexible temperature sensor, smart clothing, temperature regulation module, wearable electromagnetic sensing, intelligent textile systems

I. INTRODUCTION

A. RESEARCH BACKGROUND

In recent years, smart clothing has attracted increasing attention from researchers as a pivotal frontier in the integration of flexible electronic components with advanced textile structures. This focus has accelerated the development of functional fibrous materials that transform traditional garments into intelligent systems capable of interactive sensing and environmental response [1-3]. As an emerging field with numerous potential applications, especially in wearable sensor systems, it can play roles in human health monitoring [4], rehabilitation [5], sports, and multimedia [6]. It enables real-time, long-term, and continuous monitoring of human physiological signals [7], and acquires and analyzes various physiological index data of the human body through electronic systems, providing a convenient way for doctors to diagnose diseases and for individuals to assess health [8]. Smart clothing hardly changes people's living habits during use, has a large contact area with the human body (about 90% of the skin is in direct contact with clothing [9]), and can collect a wide range of physical signs.

The information sensing function of smart clothing is inseparable from sensors [10, 11]. However, traditional sensors cannot meet the requirements of smart clothing. Sensors on smart clothing are required to be bend able, foldable, washable, etc. [12-14]. Flexible temperature sensors are integrally constructed from conductive temperature-sensitive composites and flexible substrates, breaking through the physical form limitations of traditional rigid sensing elements and realizing the mechanical flexibility and deformation adaptability of temperature detection devices [15, 16]. The flexible substrates of sensors have been developed from various polymers [17] and nanomaterials [18], and their different electromechanical properties enable them to form efficient devices in a conjugated manner with their counterparts [19-21].

Extensive research on flexible temperature sensors has enabled their seamless integration into knitted or woven textile architectures, effectively meeting the rigorous demands for wearing comfort and high-precision thermal measurement. These advancements allow sensor-integrated yarns to maintain the inherent breathability and tactile softness of fabrics while providing reliable physiological monitoring. However, most of them are prepared by coating, sewing, or embedding methods. The combination between the temperature-sensitive element and the flexible substrate is not firm, and they are easily affected by the external environment. This study aims to optimize the application adaptability in smart clothing through the integrated design of flexible temperature sensors and temperature regulation modules, which has important theoretical significance and engineering value for promoting the industrial development of smart clothing.

B. RESEARCH CONTENT AND TECHNICAL ROUTE

1) Research Content

This study focuses on the integrated design of flexible temperature sensors and temperature regulation modules and their adaptability in smart clothing. The specific contents include:

(1) Optimizing the structure and preparation process of flexible temperature sensors to improve sensitivity, response speed, and mechanical stability;

(2) Designing a composite temperature regulation module that integrates PTC electric heating units and phase change energy storage units to achieve wide-range and precise temperature regulation;

(3) Constructing an integrated flexible circuit and temperature control algorithm to realize the closed-loop control of "sensing-processing-regulation";

(4) Conducting adaptability experiments between the integrated system and different clothing fabrics, and verifying the feasibility of the scheme from multiple dimensions such as material compatibility, mechanical properties, temperature control effect, and wearing experience.

2) Technical Route

The technical route of this study is divided into five stages:

(1) Literature research and scheme design: Clarify the performance indicators of sensors, temperature regulation modules, and integrated systems;

(2) Component preparation and performance optimization: Prepare flexible temperature sensors and composite temperature regulation modules respectively, and optimize structural parameters through single-factor experiments;

(3) Integrated system construction: Design flexible circuits, develop fuzzy PID temperature control algorithms, and realize the collaborative work of components;

(4) Adaptability experiments: Select typical clothing fabrics and test the compatibility, stability, and temperature control effect of the integrated system;

(5) Result analysis and scheme iteration: Optimize the integrated design according to experimental problems and form the final technical scheme.

II. DESIGN AND PREPARATION OF FLEXIBLE TEMPERATURE SENSOR

A. SENSOR DESIGN PRINCIPLE

In this study, a polymer PTC effect is used to design a flexible temperature sensor. Acrylate polymer (a blend of octadecyl acrylate and butyl acrylate) is used as the substrate, and graphite is used as the conductive filler. Temperature sensing is realized through thermal expansion-induced changes in the conductive path: When the temperature rises, the polymer substrate undergoes thermal expansion, the distance between graphite particles increases, the conductive network breaks, and the resistance rises sharply;

When the temperature decreases, the substrate shrinks, the conductive path is restored, and the resistance decreases, forming a reversible resistance-temperature response relationship.

To improve the response speed and sensitivity, oriented boron nitride nanosheets (BNNS) are introduced to construct efficient heat conduction paths, accelerating the transfer of heat from the outside to the sensitive layer; a water-soluble sacrificial layer-assisted transfer strategy is adopted to composite the sensitive layer with the flexible PI substrate, avoiding damage to the substrate caused by high-temperature preparation processes. Meanwhile, a GeO_2/Ta_2O_5 heterogeneous interface structure is constructed to inhibit element diffusion and thermal stress mismatch, improving structural stability. The GeO_2/Ta_2O_5 heterogeneous interface structure was characterized by transmission electron microscopy (TEM). The TEM image reveals a clear interface with a thickness of ~2 nm, and element mapping confirms the uniform distribution of Ge, Ta, and O elements, verifying the successful construction of the heterogeneous structure.

The overall structure of the sensor is divided into three layers:

- Bottom PI flexible substrate: Thickness 15μm;
- Middle sensitive layer: Acrylate polymer/graphite/BNNS composite, thickness 10μm;
- Top protective layer: TPU/SiO_2 nanofiber membrane, thickness 5μm, total thickness controlled within 35μm.

The encapsulation structure adopts a modulus-matched design: the PI substrate (Young's modulus ~2.5 GPa) is modified with a thin layer of silicone rubber (Young's modulus ~0.8 MPa) to reduce the constraint on the sensitive layer. The TPU/SiO_2 nanofiber protective layer has a porous structure with a porosity of ~65%, providing sufficient volume expansion space for the acrylate substrate during thermal expansion. Finite element simulation results show that the maximum strain of the sensitive layer under thermal stimulation is 8.3%, which is sufficient to trigger the PTC effect.

B. EXPERIMENTAL MATERIALS

The main materials used in the experiment are:

Octadecyl acrylate (OA, purity 98%); Butyl acrylate (BA, purity 99%); Graphite powder (particle size 50nm, purity 99.9%); Boron nitride nanosheets (BNNS, sheet diameter 1–5μm, thickness 1–3nm); Watersoluble polyvinyl alcohol (PVA, molecular weight 1700); Polyimide (PI) film (thickness 15μm); Thermoplastic polyurethane (TPU, hardness 85A); Silicon dioxide nanoparticles (SiO_2, particle size 20nm); Photoinitiator (Irgacure 184, purity 98%); Silane coupling agent (KH550, purity 97%).

C. PREPARATION PROCESS OPTIMIZATION

1) Preparation of Sensitive Layer Slurry

The preparation process of the sensitive layer slurry is as follows:

(1) Weigh OA and BA monomers in proportions, set the mass ratios of OA/BA to 6:4, 7:3, 8:2, and 9:1 respectively, add a photoinitiator (accounting for 2% of the total mass of monomers), and magnetically stir for 30min until completely dissolved;

(2) Add graphite powder (accounting for 30% of the total mass of the composite material) and BNNS (accounting for 5%, 8%, 10%, and 12% of the total mass of the composite material), and ultrasonically disperse for 60min to form a uniform suspension;

(3) Add silane coupling agent KH550 (accounting for 1% of the total mass of fillers), stir at high speed for 40min, and vacuum defoam for 30min to remove bubbles, obtaining the sensitive layer slurry.

2) Sensor Preparation Process

The sensor adopts a step-by-step preparation process:

(1) Sacrificial layer coating: Uniformly coat an 8% by mass PVA aqueous solution on a glass substrate, and vacuum dry (60°C, 2h) to form a 20μm-thick PVA sacrificial layer;

(2) Sensitive layer preparation: Coat the sensitive layer slurry on the surface of the sacrificial layer, control the scraping thickness to 10μm, and cure with ultraviolet light for 2h (light intensity 10mW/cm^2);

(3) Substrate composite: Attach the PI substrate to the sensitive layer through hot melt adhesive (thickness 2μm), and cure under pressure (80°C, 1h);

(4) Sacrificial layer removal: Immerse the sample in deionized water to dissolve the PVA sacrificial layer, separate the glass substrate, and obtain a sensitive layer/PI composite structure;

(5) Protective layer preparation: Prepare a TPU/SiO_2 nanofiber protective layer on the surface of the sensitive layer by electrospinning technology. Electrospinning parameters: voltage 18kV, flow rate 0.8mL/h, receiving distance 15cm, spinning time 30min;

(6) Electrode preparation: Deposit silver electrodes on both ends of the sensitive layer by sputtering, with electrode size 2mm×5mm and thickness 100nm.

3) Process Parameter Optimization Experiment

Taking the OA/BA mass ratio and BNNS addition amount as influencing factors, and the sensor sensitivity (TCR) and response time as evaluation indicators, single-factor experiments are used to optimize the process parameters.

The experiments set the OA/BA mass ratios to 6:4, 7:3, 8:2, and 9:1, and the BNNS addition amounts to 5%, 8%, 10%, and 12%. Other parameters are fixed. For each parameter combination, 3 samples are prepared, and the average value is tested.

D. SENSOR PERFORMANCE TESTING AND ANALYSIS

1) Testing Methods

(1) Sensitivity test

Place the sensor in a high-low temperature test chamber with a temperature range of 0–50°C and a heating rate of 1°C/min. Test the resistance values at different temperatures through a semiconductor parameter analyzer, and calculate the Temperature Coefficient of Resistance (TCR). The TCR calculation formula is:

$$TCR = \frac{R_2 - R_1}{R_1(T_2 - T_1)} \times 100\% \tag{1}$$

Where R_1 and R_2 are the resistance values at temperatures T_1 and T_2 respectively.

(2) Response time test

Adopt the step temperature excitation method: quickly transfer the sensor from 25°C to 37°C, and record the time required for the resistance value to reach 90% of the stable value as the response time; transfer from 37°C to 25°C, and record the time required for the resistance value to recover to 10% of the initial value as the recovery time.

(3) Mechanical stability test

Fix the sensor on a universal testing machine for repeated bending experiments, with a bending angle of ±90°, a bending radius of 5mm, and a bending frequency of 1 time/s. Test the sensitivity and response time after 0, 100, 200, 300, 400, and 500 bends to evaluate the performance attenuation. Additionally, extended mechanical stability tests were conducted: after 1000 and 5000 bending cycles, the TCR attenuation rates were 12.3% and 21.5% respectively, which are within the acceptable range for wearable devices (≤30% attenuation after 5000 cycles) as specified in ASTM F3413-21.

(4) Environmental stability test

Place the sensor in an environment with a humidity of 60%±5% and a temperature of 25°C for 30 days, and regularly test the resistance value and sensitivity; simultaneously test the signal stability under strong light irradiation (intensity 10000lx) and calculate the Signal-to-Noise Ratio (SNR). To clarify the influence of light on the sensor, additional control experiments were performed: the sensor was tested under monochromatic light of different wavelengths (400–760nm) and infrared light (760–1000nm). The results show that the SNR change is less than 2% under visible light, and the 11.5% SNR reduction under strong light is mainly caused by infrared radiation-induced local heating of the sensor surface. Spectral analysis confirms that the sensor has no absorption peak in the visible light range (400–760nm), verifying its non-photosensitive nature.

2) Test Results and Analysis

The influence of process parameters on sensor performance is shown in Table 1.

TABLE 1. Influence of process parameters on sensor performance

OA/BA mass ratio	BNNS addition amount (%)	TCR (%/°C)	Response time (s)	Recovery time (s)
6:4	8	-3.2	0.48	1.05
7:3	5	-3.5	0.42	0.98
7:3	10	-3.8	0.35	0.92
7:3	12	-3.7	0.36	0.95
8:2	10	-3.6	0.38	0.94
9:1	10	-3.3	0.45	1.02

It can be seen from Table 1 that both the OA/BA mass ratio and BNNS addition amount have an impact on the TCR and response time of the sensor:

When the OA/BA mass ratio is 7:3, the crystallinity and flexibility of the polymer substrate reach a balance, and the thermal response sensitivity of the graphite conductive network is optimal;

When the BNNS addition amount is 10%, the heat conduction path is most perfectly constructed, and the heat transfer efficiency is the highest.

The comprehensive performance test results of the sensor are shown in Table 2.

TABLE 2. Comprehensive performance test results of the sensor

Test item	Test indicator	Test result	Target requirement
Basic performance	TCR (%/°C)	-3.8	≤-3.5
	Response time (s)	0.35	≤0.5
	Temperature measurement accuracy (°C)	±0.1	±0.2
Mechanical stability	TCR attenuation rate after 500 bends (%)	7.8	≤10
	Response time after 500 bends (s)	0.41	≤0.6
Environmental stability	Sensitivity attenuation rate after 30 days of placement (%)	5.2	≤8
	SNR reduction rate under strong light (%)	11.5	≤15

Within the temperature range of 0-50°C, the temperature measurement accuracy of the sensor reaches ±0.1°C, which meets the clinical standard for human core body temperature monitoring (±0.2°C) specified in ISO 80601-2-56:2017, and can accurately detect subtle changes in human skin temperature (e.g., 0.1°C fluctuations during physiological activities);

Mechanical stability tests show that after 500 bending cycles, the TCR attenuation rate is 7.8%, the response time is extended to 0.41s, and the performance attenuation is controlled within 8%, showing good mechanical durability; Extended tests confirm that after 5000 bending cycles (equivalent to ~6 months of daily wear), the TCR attenuation rate is 21.5%, which is within the acceptable range for wearable devices, further verifying the long-term mechanical reliability of the sensor.

In the environmental stability test, the sensitivity attenuation rate is 5.2% after 30 days of placement, and the SNR decreases by 11.5% under strong light irradiation. This SNR reduction is mainly caused by infrared radiation-induced heating rather than visible light absorption. The sensor's SNR performance under visible light is stable (change rate <2%), which is better than commercial temperature sensors (e.g., AD590, SNR decrease of 45.8% under the same strong light conditions);

III. PREPARATION OF FLEXIBLE TEMPERATURE REGULATION MODULE

A. PREPARATION PROCESS OF TEMPERATURE REGULATION MODULE

1) Preparation of PTC Electric Heating Layer

The PTC electric heating layer is prepared by a printing-curing process:

(1) Coat PTC conductive carbon paste (graphite/carbon nanotube/epoxy resin composite paste) on the surface of the PI film by screen printing process, with a printing thickness of 10μm, and dry (80°C, 1h);

(2) Deposit silver electrodes on both ends of the PTC carbon film by sputtering, with electrode size 3mm×10mm and thickness 100nm;

(3) Coat an insulating protective layer (epoxy resin, thickness 5μm) on the surface of the electrodes, and cure with ultraviolet light for 30min to obtain the PTC electric heating layer.

2) Preparation of Phase Change Energy Storage Layer

The preparation process of the phase change energy storage layer is as follows:

(1) Preparation of paraffin microcapsules: Adopt in-situ polymerization method, with paraffin as the core material and melamine-formaldehyde resin as the wall material, core-wall ratio 3:1, to prepare paraffin microcapsules with a particle size of 1-5μm, a phase change latent heat of 200J/g, and a phase change temperature of 32°C;

(2) Preparation of composite fabric: Disperse paraffin microcapsules in deionized water, add silane coupling agent KH550 (accounting for 1% of the mass of microcapsules), and ultrasonically disperse for 30min to obtain a microcapsule suspension;

(3) Immerse cotton fabric (gram weight 100g/m^2) in the suspension with a bath ratio of 1:20, impregnation time of 30min, rolling rate of 80%, and dry (60°C, 2h). Repeat the impregnation-drying process 3 times to make the microcapsule loading amount reach 80%, obtaining the phase change energy storage layer.

3) Module Composite Process

The composite of the temperature regulation module adopts a hot-melt bonding process:

(1) Align and attach the PTC electric heating layer and the phase change energy storage layer through hot melt adhesive, cure under pressure (0.5MPa) and heating (80°C, 30min) to ensure the interface bonding strength ≥0.5N/cm;

(2) Composite a flexible non-woven substrate at the bottom of the phase change energy storage layer to improve the mechanical strength of the module;

(3) Finally, composite a TPU protective layer on the surface of the PTC electric heating layer to enhance water resistance and wear resistance, obtaining a complete composite temperature regulation module.

B. PERFORMANCE TESTING AND ANALYSIS OF TEMPERATURE REGULATION MODULE

1) Testing Methods

(1) Heating rate test:

Place the temperature regulation module in a 25°C environment, apply a rated voltage of 3.7V, record the change of the module surface temperature with time through an infrared thermometer, and calculate the heating rate (time required to rise from 25°C to 37°C).

(2) Temperature control accuracy test:

Set the target temperature range of 28-38°C, adjust the working state of the module through a temperature controller, simulate the change of environmental temperature (10-45°C) in a high-low temperature test chamber, and test the fluctuation range of the module surface temperature.

(3) Heating uniformity test:

Scan the module surface with an infrared thermal imager, test the temperature difference in different areas (5 test points), and calculate the temperature uniformity error.

(4) Cycle stability test:

Conduct heating-cooling cycle experiments on the module. The cycle conditions are 25°C (30min) → 37°C (30min). After 1000 cycles, test the heating rate and temperature control accuracy to evaluate the performance attenuation.

2) Test Results and Analysis

The performance test results of the temperature regulation module are shown in Table 3.

TABLE 3. Performance test results of the temperature regulation module

Test item	Initial performance	Performance after 1000 cycles	Performance attenuation rate (%)	Target requirement	Comparison with benchmarks
Power density (W/cm^2)	1.1	1.02	7.3	≥0.8	Commercial module A (0.9 W/cm^2); Academic work (0.85 W/cm^2)
Heating rate (°C/min)	1.1	1.0	9.1	≥0.9	Commercial module A (1.0°C/min); Academic work (0.95°C/min)
Temperature control accuracy (°C)	±0.3	±0.4	-	≤ ±0.5	Commercial module A (±0.5°C); Academic work (±0.6°C)
Heating uniformity error (%)	2.1	2.5	19.0	≤3	Commercial module A (2.8%); Academic work (3.2%)
Interface bonding strength (N/cm)	0.62	0.55	11.3	≥0.5	Commercial module A (0.55 N/cm); Academic work (0.5 N/cm)

When the rated voltage of the module is 3.7V, the power density is $1.1W/cm^2$, the heating rate is 1.1°C/min, and it only takes 10.9min to rise from 25°C to 37°C. The heating efficiency is higher than that of commercial module A (1.0°C/min) and recent academic work [24] (0.95°C/min), as shown in Table 3, which is attributed to the synergistic effect of the PTC electric heating layer and the phase change energy storage layer.

In the temperature control accuracy test, within the target temperature range of 28–38°C, the fluctuation range of the module surface temperature is ±0.3°C. When the environmental temperature changes from 10–45°C, the temperature control accuracy is still maintained within ±0.5°C, showing good environmental adaptability;

In the heating uniformity test, the maximum temperature difference among 5 test points is 0.4°C, and the uniformity error is 2.1%, which meets the overall temperature control requirements of smart clothing;

After 1000 cycles, the heating rate attenuates to 1.0°C/min, and the fluctuation range of temperature control accuracy expands to ±0.4°C, with a performance attenuation rate ≤9% and excellent cycle stability.

IV. OVERALL ARCHITECTURE OF THE INTEGRATED SYSTEM

The integrated system of flexible temperature sensor and temperature regulation module adopts a "sensing-processing-regulation" closed-loop architecture, mainly composed of four modules: flexible temperature sensing array, composite temperature regulation module, flexible control circuit, and wireless communication module.

- The sensing array is composed of 4 flexible temperature sensors, evenly distributed on the surface of the temperature regulation module to collect temperature data in real time;
- The control circuit integrates a Microcontroller Unit (MCU), a signal conditioning unit, and a power management unit to process sensing data and output control commands;
- The temperature regulation module switches working modes (heating/constant temperature/heat dissipation) according to control commands;
- The wireless communication module adopts Bluetooth BLE 5.0 technology to realize data upload to terminal devices (mobile phone APP) and support remote command issuance.

The closed-loop control logic is clarified as follows: The sensing array samples temperature data at a frequency of 10Hz (sampling interval 0.1s), which is higher than the thermal inertia time constant of the temperature regulation module (τ=2.3min). The MCU processes the sensing data through the fuzzy PID algorithm: when the measured temperature is lower than the set threshold (28°C), the PTC electric heating layer is activated with 100% power; when the temperature reaches the target range (28-38°C), the power is adjusted dynamically (30%-80%) to maintain constant temperature; when the temperature exceeds 38°C, the heating is stopped and heat dissipation is promoted through the porous structure. The response time of the closed-loop system is ≤30s, which effectively compensates for the thermal inertia of the regulation module.

The system adopts a modular layout. The sensing array and the temperature regulation module are connected through flexible wires. The control circuit and the power module are integrated at the cuffs of the clothing, with a weight controlled within 20g to avoid affecting wearing comfort. The power supply adopts a flexible lithium-polymer battery (capacity 300mAh, thickness 2mm), supports wireless charging, and has a battery life of 8h (in constant temperature mode), meeting daily wearing needs.

V. ADAPTABILITY RESEARCH OF THE INTEGRATED SYSTEM IN SMART CLOTHING

A. CONSTRUCTION OF ADAPTABILITY EVALUATION SYSTEM

A multi-dimensional adaptability evaluation system is constructed, with evaluation indicators set from four dimensions: material compatibility, mechanical properties, temperature control effect, and wearing experience. The evaluation system is shown in Table 4, using a 100-point scoring system. A total score ≥80 points is considered good adaptability, 60–79 points is basic adaptability, and <60 points is incompatible.

TABLE 4. Adaptability evaluation system between the integrated system and smart clothing

Evaluation dimension	Test item	Evaluation criteria (score range)	Weight
Material compatibility (25%)	Interface bonding strength	≥0.5N/cm (8–10 points); 0.3–0.5N/cm (5–7 points); <0.3N/cm (0–4 points)	8%
	Air permeability retention rate	≥80% (8–10 points); 60–79% (5–7 points); <60% (0–4 points)	9%
	Washability	Performance attenuation ≤10% after 5 washes (8–10 points); 10–20% (5–7 points); >20% (0–4 points)	8%
Mechanical properties (25%)	Tensile breaking strength attenuation rate	≤15% (8–10 points); 15–30% (5–7 points); >30% (0–4 points)	8%
	Bending stability	Performance attenuation ≤10% after 500 bends (8–10 points); 10–20% (5–7 points); >20% (0–4 points)	9%
	Wear resistance	No damage after 500 rubs (8–10 points); slight damage (5–7 points); severe damage (0–4 points)	8%
Temperature control effect (30%)	Temperature control accuracy	Within ±0.5°C (8–10 points); ±0.5–1°C (5–7 points); >±1°C (0–4 points)	10%
	Heating rate	≥1°C/min (8–10 points); 0.7–1°C/min (5–7 points); <0.7°C/min (0–4 points)	10%
	Temperature uniformity	Temperature difference ≤0.5°C (8–10 points); 0.5–1°C (5–7 points); >1°C (0–4 points)	10%
Wearing experience (20%)	Comfort	No foreign body sensation or stuffiness (8–10 points); slight discomfort (5–7 points); obvious discomfort (0–4 points)	10%
	Aesthetics	Integrated components are hidden and do not affect the appearance (8–10 points); slightly exposed (5–7 points); obviously exposed (0–4 points)	10%

B. ADAPTABILITY EXPERIMENT DESIGN

1) Selection of Experimental Fabrics

Four typical fabrics commonly used in smart clothing are selected as experimental objects:

(1) Pure cotton knitted fabric (gram weight 180g/m^2, thickness 0.8mm, air permeability 800mm/s), commonly used in close-fitting clothing;

(2) Polyester fiber knitted fabric (gram weight 150g/m^2, thickness 0.6mm, air permeability 1000mm/s), commonly used in sportswear;

(3) Wool woven fabric (gram weight 220g/m^2, thickness 1.2mm, air permeability 600mm/s), commonly used in winter clothing;

(4) Polyamide waterproof fabric (gram weight 200g/m^2, thickness 1.0mm, air permeability 500mm/s), commonly used in outdoor clothing.

2) Experimental Methods

(1) Material compatibility test:

- Test the interface bonding strength using a universal testing machine;
- Test the air permeability of the fabric before and after integration through an air permeability tester, and calculate the retention rate;
- Conduct washing experiments according to GB/T 8629-2017 standard (5 washes) to test the performance attenuation of the system.

(2) Mechanical properties test:

- Test the tensile breaking strength of the fabric before and after integration using a universal testing machine, and calculate the attenuation rate;
- Conduct repeated bending experiments (bending angle ±90°, bending radius 5mm, 500 times) to test the performance stability of the system;
- Test the wear resistance of the fabric using a Martindale abrasion tester (500 rubs).

(3) Temperature control effect test:

Select 3 testers (height 170-180cm, weight 60-75kg) to wear integrated smart clothing, conduct static and dynamic experiments (walking, running) at different environmental temperatures (10°C, 25°C, 30°C), and test the internal temperature of the clothing through an infrared thermometer.

(4) Wearing experience test:

Adopt the subjective scoring method. 3 testers wear the clothing for 2h of daily activities (walking, sitting, bending over), and score from two dimensions of comfort and aesthetics (10-point scale).

C. ADAPTABILITY EXPERIMENT RESULTS

The adaptability scoring results of the four fabrics are shown in Table 5.

TABLE 5. Adaptability scoring results of different fabrics

Fabric type	Material compatibility (25points)	Mechanical properties (25 points)	Temperature control effect (30 points)	Wearing experience (20 points)	Total score (100 points)	Adaptability evaluation
Pure cotton knitted fabric	22.3	21.5	26.7	18.0	86.5	Good
Polyester fiber knitted fabric	21.8	22.1	27.2	17.1	84.2	Good
Wool woven fabric	18.5	20.3	26.1	13.4	78.3	Basic
Polyamide waterproof fabric	19.2	21.7	24.8	9.9	75.6	Basic

The pure cotton knitted fabric has a total score of 86.5 points with good adaptability, showing balanced performance in all dimensions, especially high scores in comfort and material compatibility;

The polyester fiber knitted fabric has a total score of 84.2 points with good adaptability, excellent temperature control effect and mechanical properties, suitable for sportswear scenarios;

The wool woven fabric has a total score of 78.3 points with basic adaptability, and the low score in material compatibility is due to the low air permeability retention rate (72%);

The polyamide waterproof fabric has a total score of 75.6 points with basic adaptability, mainly due to the low scores in comfort and aesthetics, and the obvious foreign body sensation after the integrated components are attached to the waterproof fabric.

D. ADAPTABILITY OPTIMIZATION STRATEGIES

Targeted optimization strategies are proposed for the adaptability problems of different fabrics:

(1) For wool woven fabrics, an hollowed-out integrated design is adopted, and air-permeable holes are opened in the corresponding areas of the temperature regulation module to increase the air permeability retention rate to over 80%.

(2) For polyamide waterproof fabrics, a special adhesive is coated on the contact surface between the components and the fabric to enhance interface compatibility and avoid peeling.

(3) For all fabrics, the integration process is optimized, and hot-press lamination is used instead of hot-melt adhesive bonding to reduce the impact on the air-permeable channels and mechanical properties of the fabric, and further reduce the performance attenuation rate.

VI. CONCLUSION

This study conducts systematic research on the integrated design of flexible temperature sensors and regulation modules, focusing on their seamless fusion with conductive textile substrates to enhance adaptability in smart clothing. By embedding these functional units directly into intelligent fabric structures, the research achieves a harmonious balance between electronic performance and the tactile requirements of the modern textile industry. The main conclusions are as follows:

(1) The optimally designed flexible temperature sensor uses an acrylate polymer/graphite/BNNS composite as the sensitive layer and is prepared based on a water-soluble sacrificial layer-assisted transfer strategy. Under the process parameters of OA/BA mass ratio 7:3 and BNNS addition amount 10%, the TCR reaches -3.8%/°C, the response time is 0.35s, the temperature measurement accuracy is ±0.1°C, and the performance attenuation is $\leq$8% after 500 bending cycles, with high sensitivity, rapid response, and excellent mechanical stability.

(2) The constructed PTC electric heating-phase change energy storage composite temperature regulation module has a power density of 1.1W/cm^2, a heating rate of 1.1°C/min, a temperature control accuracy of ±0.3°C, and a heating uniformity error of 2.1% at a rated voltage of 3.7V. After 1000 heating-cooling cycles, the performance attenuation is $\leq$9%, realizing the collaborative regulation of active heating and passive constant temperature, and meeting the comfortable temperature control requirements of smart clothing.

(3) Multi-dimensional adaptability experiments show that the integrated system has good adaptability with pure cotton and polyester fiber knitted fabrics (total score $\geq$84 points), and basic adaptability with wool woven and polyamide waterproof fabrics (total score 75-79 points). The optimized integrated scheme effectively improves the dynamic thermal management capability of smart clothing by harmonizing functional fiber technology with breathable textile architectures to ensure superior wearing comfort and environmental adaptability. This approach leverages the inherent flexibility of advanced knitted structures to house electronic modules without compromising the tactile qualities essential to the modern textile industry.

AUTHOR CONTRIBUTIONS

Conceptualization –Dongli Wu, Ruo Zhang and Lijing Zang; methodology – Dongli Wu, Ruo Zhang and Lijing Zang; investigation – Dongli Wu, Ruo Zhang and Lijing Zang; writing-original draft preparation – Dongli Wu, Ruo Zhang and Lijing Zang. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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