INTRODUCTION

Clothing serves as the vital interface between the human body and the surrounding environment, playing a pivotal role in the regulation of body heat to ensure daily thermal comfort. In the face of fluctuating ambient temperatures, failure to adapt can result in thermal discomfort or even adverse health effects.

Thermoregulatory clothing emerges as a solution not only for personal well-being but also for optimizing indoor building energy consumption. With over 50% of total building energy use attributed to the heating, ventilation, and air-conditioning (HVAC) system, the development of clothing capable of reducing heating set points or increasing cooling set points holds significant promise for energy savings.

Distinguishing between active and passive types, thermoregulatory clothing aims to balance heating and cooling capabilities. Passive types, requiring no external power, are particularly appealing. However, many existing solutions, activated post-sweating, may cause wet discomfort. The challenge lies in developing clothing that responds to temperature changes without this discomfort. Current technologies like phase-change materials, thermo-responsive hydrogels, and shape-memory polymers show limited efficacy in regulating multiple heat dissipation pathways simultaneously.

Addressing these challenges, the proposed temperature-adaptive clothing integrates metalized polyethylene actuators for multimodal body thermal regulation, encompassing radiation, convection, and sweat evaporation. The metal layer not only facilitates temperature-responsive actuation but also induces radiative heating. Evaluation through thermal manikin tests and thermo-physiological modelling demonstrates the clothing's potential to decrease heating set points and increase cooling set points, translating to over 30% savings in building cooling and heating energy. The scalability of this solution, utilizing cost-effective materials, further enhances its viability for widespread adoption.

BASIC TERMINOLOGIES FOR THERMOCLOTHING

Significance of Thermoregulatory Clothing: It plays a crucial role in maintaining body thermal comfort and contributes to building energy savings amidst changing environmental conditions.

Limitations of Existing Solutions: Current temperature-adaptive clothing lacks effective thermoregulation due to its inability to simultaneously regulate multiple heat-dissipation pathways, limiting its power.

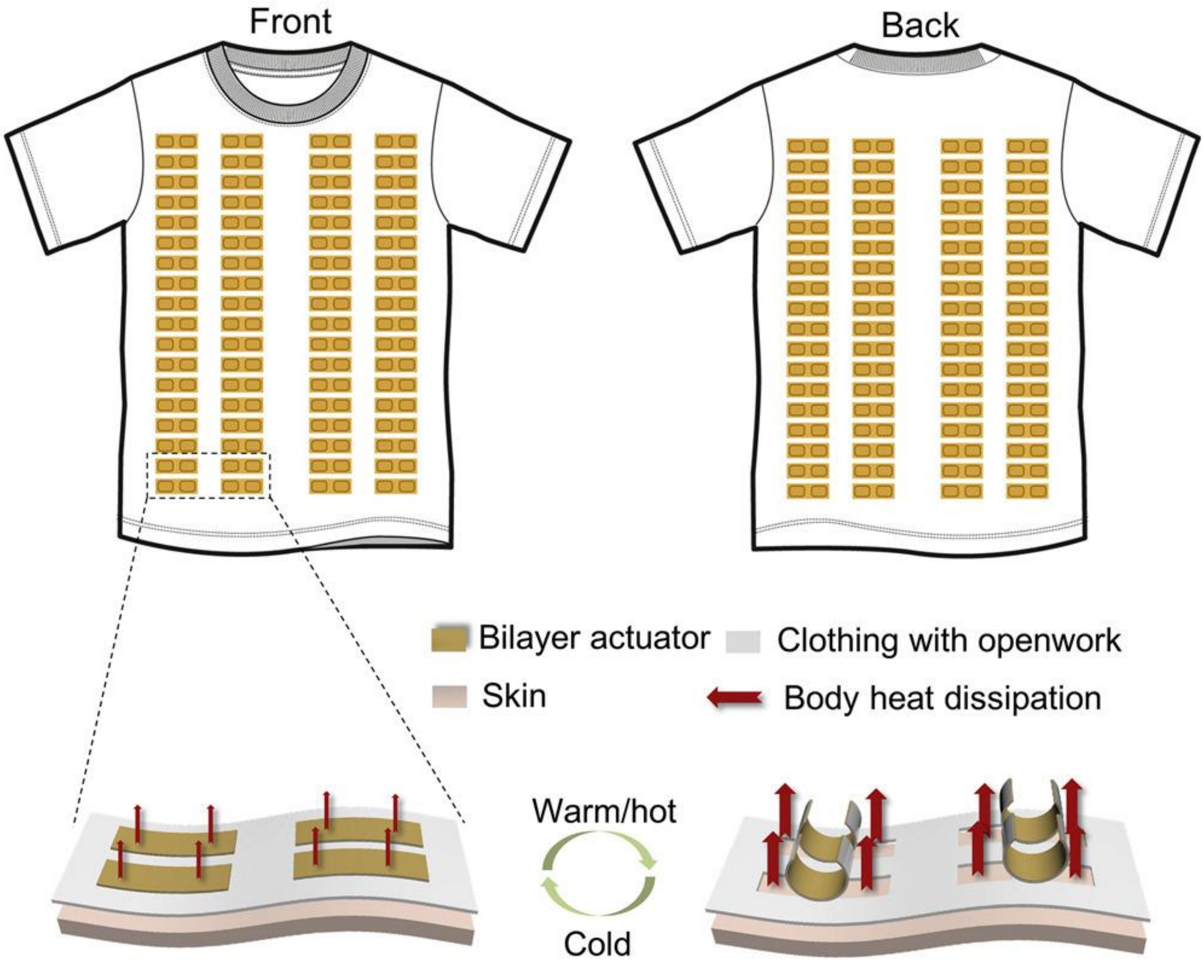
Innovative Approach: The presented solution introduces thermoregulatory clothing with temperature-adaptive multimodal body-heat regulation, encompassing convection, radiation, and sweat evaporation.

Key Features: The clothing, equipped with metalized polyethylene actuators, demonstrates automatic adaptation to temperature changes (15°C–35°C) within seconds.

Testing and Validation: Thermal manikin tests and thermo-physiological modelling substantiate the effectiveness of the clothing. It expands the comfort zone by over 2°C on both cold and hot sides.

Energy Efficiency: The designed clothing showcases a potential 30% building energy savings when applied in indoor environments, highlighting its impact on sustainable practices.

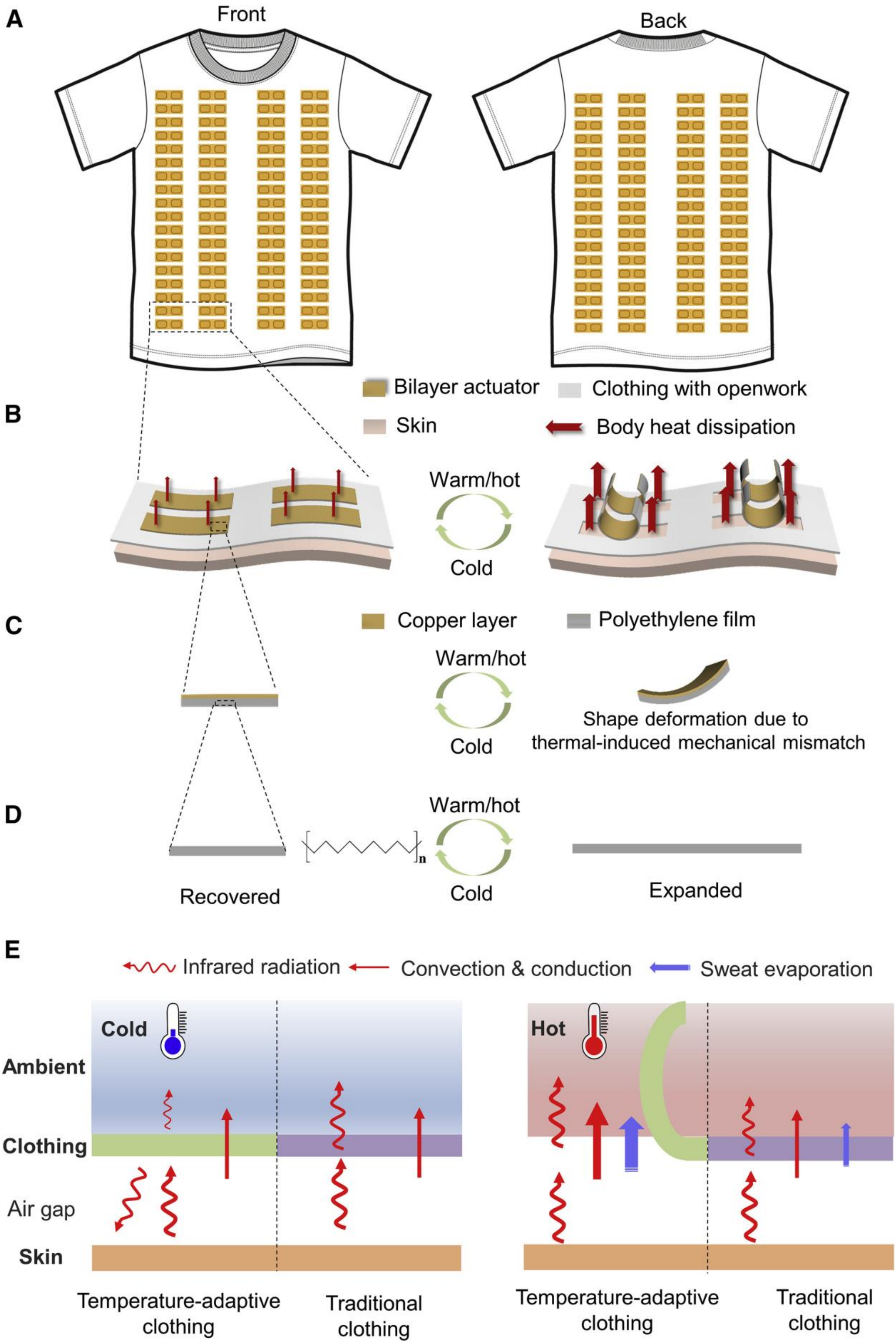
Enhanced Wearable Experience: In addition to energy efficiency, the smart clothing significantly improves wearer comfort and performance, especially in the face of fluctuating or extreme environmental conditions.


Front
Back
Bilayer actuator
Clothing with openwork
Skin
Body heat dissipation
Warm/hot
Cold

THERMOCLOTHING MODEL

Thermoregulatory clothing employs a unique working principle rooted in the thermal expansion and contraction properties of polyethylene (PE), a material with a significantly higher linear thermal expansion ratio than conventional textile materials like nylon and polyester. The clothing features a knitted design with rectangular openwork on its front and back sides, housing actuators that cover the openwork. These actuators, composed of a bilayer structure with a deposited copper layer onto the PE film, act as temperature-responsive components. In hot ambient conditions, the PE film expands more than the copper layer due to their disparate thermal expansion ratios. This thermal-induced mechanical mismatch causes the bilayer actuator to bend towards the ambient, facilitating enhanced body heat dissipation through improved infrared radiation transmission, air convection, and sweat evaporation.

Conversely, in cold ambient temperatures, the metalized PE film actuator returns to its original flat shape. In this state, it reflects infrared body radiation back to the skin while suppressing the infrared radiation from the outer surface, thereby minimizing body-heat dissipation and promoting warmth. This dynamic response allows the clothing to adapt seamlessly to changing environmental conditions. Traditional textiles, such as cotton, lack this sophisticated mechanism, hindering effective body-heat regulation. The proposed thermoclothing thus exemplifies a groundbreaking approach to achieving both cooling and warming effects based on the ingenious interplay of materials and their thermal properties.


A
Front
Back
B
Bilayer actuator
Clothing with openwork
Skin
Body heat dissipation
Warm/hot
Cold
C
Copper layer
Polyethylene film
Warm/hot
Cold
Shape deformation due to
thermal-induced mechanical mismatch
D
Warm/hot
n
Cold
Recovered
Expanded
E
Infrared radiation
Convection & conduction
Sweat evaporation
Cold
Hot
Ambient
Clothing
Air gap
Skin
Temperature-adaptive clothing
Traditional clothing
Temperature-adaptive clothing
Traditional clothing

BENDING PROPERTY OF THE ACTUATOR

The bending property of the heterogeneous bilayer actuator is pivotal for achieving multimodal personal thermal regulation. Bending angles were measured under varied PE-film and copper-layer thicknesses across different ambient temperatures using a hotplate within an environmental chamber. With a 40 nm copper layer, the impact of PE film thicknesses (0.04, 0.06, 0.08, and 0.1 mm) revealed that 0.04 mm achieved the maximum bending angle at 35°C. Further investigation with different copper-layer thicknesses (40, 100, 800, and 4,000 nm) showed a nonmonotonic trend in bending angles at higher temperatures. Theoretical calculations and numerical simulations aligned with experimental results, explaining the interplay between thermal expansion, layer stiffness, and bending angles. The optimal sample (Cu800) exhibited rapid response (9 s) to temperature changes and maintained stability after 500 cycles. The open-area ratio, representing the percentage of uncovered skin, demonstrated effective body-heat dissipation in warm ambient conditions. These findings underscore the actuator's suitability for adaptive thermal regulation in diverse environmental conditions.

INFRARED OPTICAL PROPERTY OF THE ACTUATOR

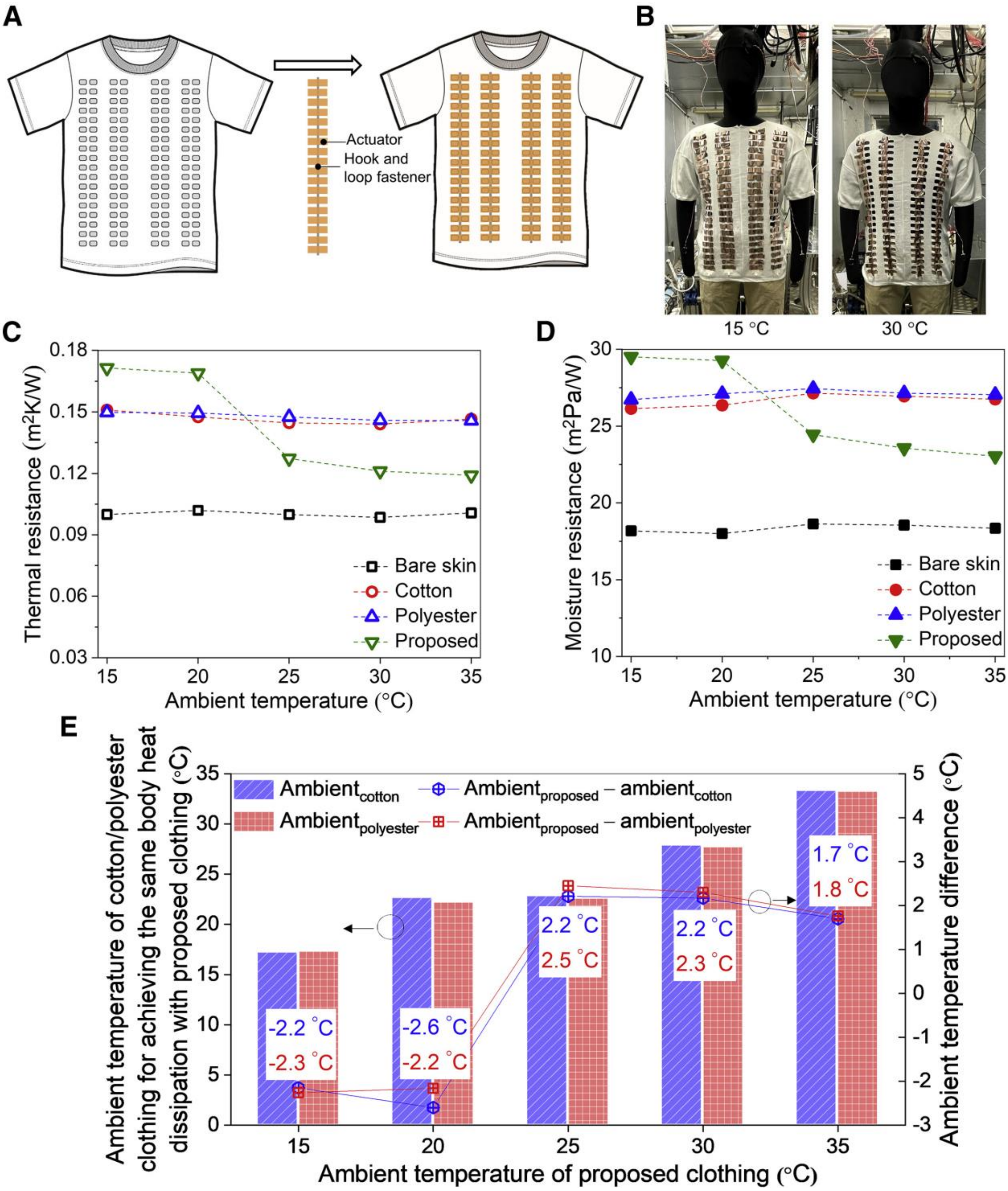
The infrared optical properties of the actuator play a crucial role in achieving radiative cooling and heating effects in temperature-adaptive clothing. In the open state, the actuator allows body radiation to transmit into the ambient, achieving radiative cooling. Conversely, in the closed state, radiative heating occurs due to the mid-infrared optical properties of both the PE film and the metal layer. The PE film, being infrared-transparent, reflects body radiation back to the skin, demonstrating high mid-infrared reflectance, around eight times higher than conventional fabrics like cotton and polyester. This feature enhances thermal insulation. Simultaneously, the copper layer exhibits low mid-infrared emissivity, nearly 10 times smaller than conventional fabrics, effectively suppressing heat dissipation from the textile to the ambient. The combined effects of high reflectance on the inner surface and low emissivity on the outer surface result in promising radiative heating effects, demonstrating the potential of the proposed temperature-adaptive clothing in regulating body thermal comfort.

THERMAL PERFORMANCE EVALUATION OF THE TEMPERATURE ADAPTIVE CLOTHING

The thermal performance evaluation of temperature-adaptive clothing involves knitting a fabric with rectangular openwork using polyester yarns and integrating actuators through hook and loop fasteners. T-shirts made of conventional cotton and polyester, along with the temperature-adaptive textile, are tested on a perspiring thermal manikin. The clothing exhibits temperature-responsive thermal and moisture resistances, showing larger resistances in cold conditions (indicating warming effects) and smaller resistances in warm conditions (indicating cooling effects).

A validated thermo-physiological model is employed to estimate heat dissipation. The model considers the physiological response to ambient changes, such as increased sweat production in higher temperatures. The temperature-adaptive clothing, with its mechanical and optical properties, influences heat dissipation, leading to responsive resistances. Calculations indicate that the proposed clothing allows for a lower heating set point in cold conditions and a higher cooling set point in hot conditions compared to conventional cotton and polyester clothing.

The overall result is an expansion of the comfort zone by 4.3°C, translating to over 30% building cooling and heating energy savings. This innovation holds promise for achieving effective personal thermal regulation and enhancing energy efficiency in various ambient conditions.


A
B
Actuator
Hook and
loop fastener
15 °C
30 °C
C
Thermal resistance (m²K/W)
Ambient temperature (°C)
Bare skin
Cotton
Polyester
Proposed
D
Moisture resistance (m²Pa/W)
Ambient temperature (°C)
Bare skin
Cotton
Polyester
Proposed
E
Ambient temperature of cotton/polyester clothing for achieving the same body heat dissipation with proposed clothing (°C)
Ambient temperature difference (°C)
Ambient temperature of proposed clothing (°C)
Ambient_cotton
Ambient_polyester
Ambient_proposed – ambient_cotton
Ambient_proposed – ambient_polyester
-2.2 °C
-2.3 °C
-2.6 °C
-2.2 °C
2.2 °C
2.5 °C
2.2 °C
2.3 °C
1.7 °C
1.8 °C

THERMAL MENIKIN TEST

Researchers used a special kind of mannequin, called a thermal manikin, to test how well different types of clothing handle heat and moisture in different temperatures. This manikin is designed to mimic a human body and can help simulate how our bodies interact with the surrounding environment.

PROCEDURE:

Set-up: They put the thermal manikin in a big room with controlled temperature and humidity (like a big box). The manikin was filled with water, and they used electric heaters inside it to control its temperature.

Controlled Temperature: They wanted to see how the clothing performs in different temperatures, so they tested it at 15°C, 20°C, 25°C, 30°C, and 35°C.

Clothing Types: They tested three types of clothing:

- Bare Skin: Just the manikin without any clothes.
- Traditional Clothing: Clothes made of typical materials like cotton and polyester.

- Temperature-Adaptive Clothing: Special clothing designed to adjust to different temperatures.

Measuring Heat and Moisture: They used a computer to measure how much heat and moisture was being transferred when the manikin was wearing different types of clothes in each temperature.

Controller: They used a controller to make sure the manikin's skin stayed at a constant temperature (35°C) during the tests.

Recording Data: They recorded the power needed to maintain the manikin's temperature for each case.

Analysis: With this data, they calculated how well each type of clothing resisted heat and moisture under different temperature conditions.

CONCLUSION:

In conclusion, the developed temperature-adaptive clothing, featuring metalized polyethylene actuators, offers a groundbreaking solution for multimodal body-heat regulation. By incorporating mechanisms that modulate radiation, convection, and sweat evaporation, the clothing demonstrates a significant reduction in heating set point by 2.3°C in cold conditions and an increase in cooling set point by 2.0°C in hot conditions when compared to conventional cotton and polyester clothing. This innovation translates to over 30% building cooling and heating energy savings. Notably, the clothing maintains wearer comfort during environmental transitions, showcasing its adaptability.

The advantages of the proposed clothing include its lightweight design (306.2 g), cost-effectiveness, and applicability in the temperature range of 15°C–35°C. The actuator's highly repeatable temperature-responsive behaviour and stability over 500 cycles further validate its practical use. Future endeavours aim to enhance the aesthetic aspects of the clothing, exploring diverse colors and geometric patterns for both actuators and supporting textiles.