processes

*Review*

# Personal Wearable Thermal and Moisture Management Clothing: A Review on Its Recent Trends and Performance Evaluation Methods

**Junming Zhou [1], Jinming Zhao [1], Xiaolei Guo [1], Yuxing Hu [1], Xiaofeng Niu [1,*] and Faming Wang [2]**

[1] College of Urban Construction, Nanjing Tech University, Nanjing 211816, China; junmingzhou@njtech.edu.cn (J.Z.); 202261224064@njtech.edu.cn (J.Z.); 202361224073@njtech.edu.cn (X.G.); 202161224021@njtech.edu.cn (Y.H.)
[2] Division Animal and Human Health Engineering, Department of Biosystems (BIOSYST), KU Leuven, Kasteelpark Arenberg 30, BE-3001 Leuven, Belgium; faming.wang@kuleuven.be
* Correspondence: newton@njtech.edu.cn

**Abstract:** Personal wearable systems designed to manage temperature and moisture are gaining popularity due to their potential to enhance human thermal comfort, safety, and energy efficiency, particularly in light of climate change and energy shortages. This article presents the mechanisms of thermal and moisture management, recent advances in wearable systems for human thermal and moisture management, and methods for their performance evaluation. It evaluates the pros and cons of various systems. The study finds that most wearable systems for thermal and moisture management are being examined as individual topics. However, human heat and moisture management have noteworthy interactions and impacts on human thermal comfort. There are certain limitations in the methods used for evaluating personal heat and moisture management in wearable systems. This review suggests future research directions for wearable systems to advance this field and overcome these limitations.

**Keywords:** high-temperature and high-humidity environments; wearable clothing; thermal and moisture management; performance evaluation indicators

check for updates

**Citation:** Zhou, J.; Zhao, J.; Guo, X.; Hu, Y.; Niu, X.; Wang, F. Personal Wearable Thermal and Moisture Management Clothing: A Review on Its Recent Trends and Performance Evaluation Methods. *Processes* **2023**, *11*, 3063. https://doi.org/10.3390/pr11113063

Academic Editors: Zhanxiao Kang, Qing Chen and Blaž Likozar

Received: 6 October 2023
Revised: 19 October 2023
Accepted: 24 October 2023
Published: 25 October 2023



## 1. Introduction

Personnel working in high-temperature and high-humidity environments, such as outdoor medical personnel, workers in mining, metallurgy, and other industries who need to wear heat-protective clothing, as well as firefighters, are not equipped with air conditioning and other temperature-control devices due to the limitations of the workplace. In addition, these personnel are also required to carry out high-intensity labor, which is prone to generating excessive heat and then forming a high-temperature and high-humidity microenvironment, resulting in uncompensated heat stress [1]. Physiological studies indicate that high-temperature environments can decrease human concentration and execution, while also triggering a sense of anxiety, which can significantly impact work efficiency. Additionally, if body temperature exceeds 39 °C, individuals are at risk of a heatstroke, and at a temperature of 40.6 °C, it can be life-threatening, as demonstrated in Figure 1 [2]. Therefore, maintaining a constant human body temperature not only ensures work efficiency but is also an important prerequisite for good health. In the face of the growing demand for personal cooling/dehumidification, the concept of personal thermal and moisture management wearable systems has been proposed [3]. Personal thermal and moisture management wearable systems are one of the common solutions to protect the body from heat stress, especially for those who work in hot and humid areas, which is considered to be an effective personal protection measure [4].

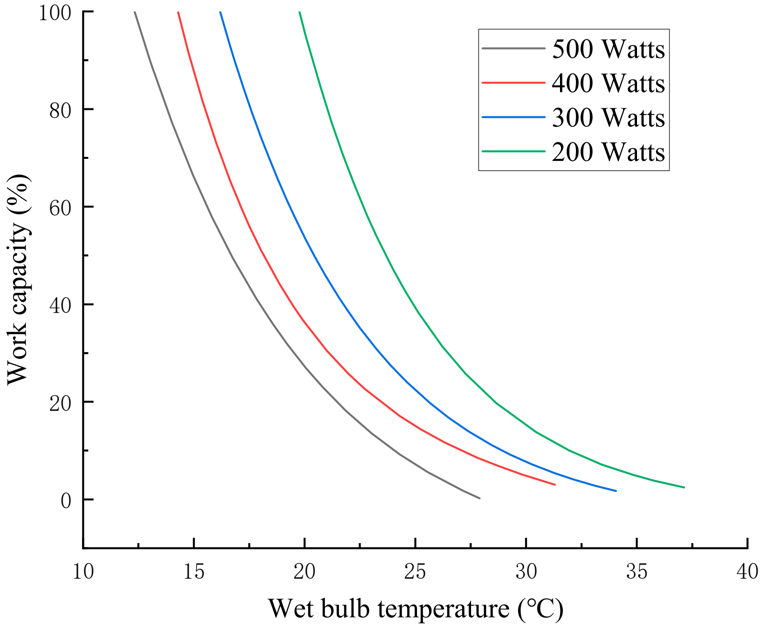



**Figure 1.** Association between work capacity and wet bulb temperature for different work intensities.

The human body maintains its thermal equilibrium through the transfer of heat and sweat, which can occur via four primary pathways: thermal conduction, thermal convection, thermal radiation, and evaporation, as illustrated in Figure 2 [5]. Many personal thermal and moisture management wearable systems have been designed for human temperature and humidity regulation [6]. These devices can improve thermal comfort for the human body and provide better temperature and humidity control in hot and humid environments. These mechanisms play a crucial role in regulating body temperature and ensuring optimal physiological functioning. The development of these wearable systems represents a significant advancement in the field of personal thermal management [7]. By optimizing heat and moisture transfer, these devices can help individuals maintain a comfortable body temperature and mitigate the risk of heat-related ailments. Additionally, they have the potential to enhance overall well-being and performance in various settings, including sports, occupational environments, and daily activities [8,9].

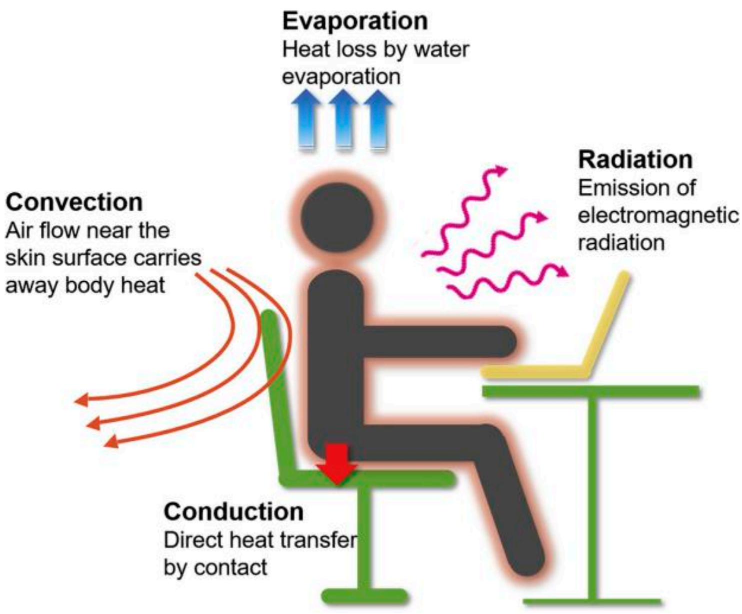



**Figure 2.** Personal thermal and moisture management [5].

In this paper, we explore the design, functionality, and performance of these personal thermal and moisture management wearable systems. We examine their potential benefits and limitations, discuss the underlying principles of heat and moisture transfer, and present recent advancements in this rapidly evolving field. Through a comprehensive analysis, we aim to shed light on the significance of these wearable technologies and their potential applications in improving human thermal comfort and well-being.

## 2. Thermal and Moisture Management Mechanism

The human–clothing–environment heat and moisture transfer mechanism includes both heat and moisture transfer. When talking about human heat and moisture management, clothing plays an important role in this process.

### *2.1. Thermal Transfer Mechanism*

Heat transfer from the human body surface to the environment is a complex and variable process involving the interaction of several factors. Among them, the air layer between the skin and the garment, the thermal conductivity properties of the garment material, and the heat transfer from the air layer between the garment and the environment are the key elements. The modes of heat transfer include conduction, convection, radiation, and evaporative heat dissipation, which interact and work together to influence the heat exchange process between the body and the environment.

Clothing plays a crucial role in the heat exchange between the human body and the environment, and it can provide thermal insulation and heat preservation. In order to better understand the heat transfer performance of garments, researchers have abstracted and idealized the heat transfer process of garments, thus establishing garment heat transfer models, as shown in Figure 3. However, these models do not fully reflect the situation of real human beings wearing garments, because the heat exchange between the human body and the environment is very complex in real situations.

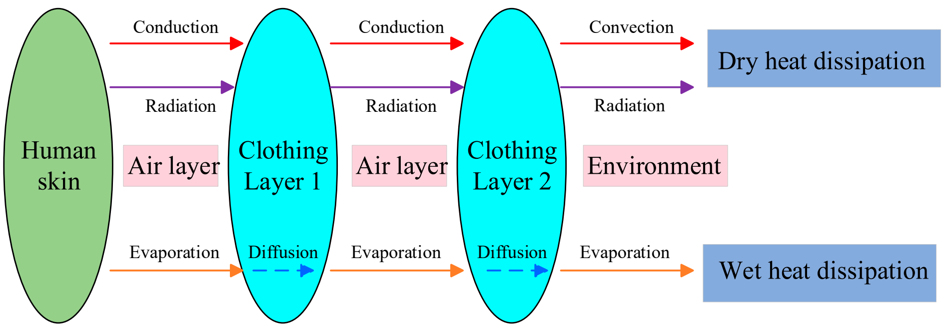



**Figure 3.** Thermal transfer mechanism of clothing.

When the human body wears looser clothing, is in a state of motion, or is in an environment with high airflow velocities, there is not only conduction and radiation but also convective heat dissipation between the human body and the clothing and the air layer between the clothing and the clothing. In addition, convective heat dissipation also occurs between the air layer and the environment, and when the garment material is fluffy, radiative heat dissipation also occurs within the garment. Therefore, in order to evaluate the heat transfer performance of garments more comprehensively, researchers have proposed the concept of garment thermal resistance [10]. Garment thermal resistance integrates several factors, including the heat transfer performance of the garment material, the heat transfer performance of the air layer between the body and the garment, the fit of the garment to the body, and the flow of the air layer within the garment. By measuring the size of the thermal resistance of a garment, we were able to evaluate the heat transfer performance of the garment more comprehensively [11]. It is worth noting that current cooling suits can put the human body in a comfortable temperature range, but there still is a risk of condensation, putting the human skin in a wet environment; thus, humidity control is particularly important.

## 2.2. Moisture Transfer Mechanism

Water exists on the surface of human skin in two forms: gaseous and liquid. When water spreads through a garment into the environment, the process is known as the moisture permeability of the garment. Moisture permeability is the diffusion of water from the surface of the human body into the environment through both the openings of the garment and the fabric of the garment. Figure 4 shows a schematic diagram of the moisture permeation of a garment, which includes the pathways of moisture transfer.

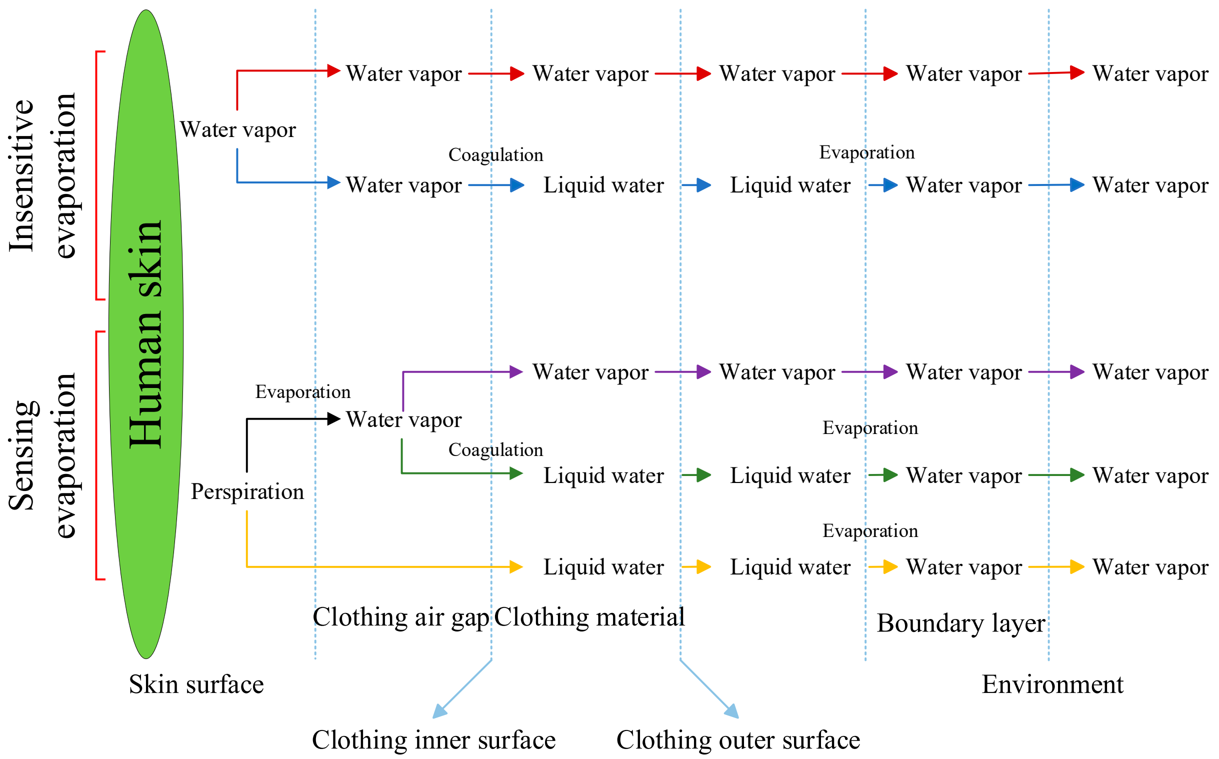



**Figure 4.** Moisture transfer mechanism of clothing.

In order to assess the moisture permeability of garments, commonly used indicators are the garment moisture resistance and the moisture permeability index [12]. The garment moisture resistance is the degree to which a garment impedes the diffusion of water, i.e., the ability of the garment material to block water. The moisture permeability index is a measure of the moisture permeability of a garment, which takes into account the moisture resistance of the garment and the rate of diffusion of water vapor. The higher the moisture permeability index, the better the moisture permeability of the garment and the more effective the transfer of moisture from the surface of the human body to the environment.

By studying the moisture-wicking properties of garments, we can design and select garments that are more appropriate for different environmental conditions and activity levels. In addition, garments with good moisture-wicking properties can help the human body stay dry and comfortable inside special garments that are airtight (e.g., epidemic-proof garments, firefighting garments), reducing the retention of perspiration on the surface of the skin and thus providing a better wearing experience [13]. This is of great importance for firefighters, outdoor workers, and people in everyday life. Therefore, studying the moisture permeability and wicking properties of garments is a key step in improving the comfort and functionality of garments.

## 3. Classification and Characteristics of Thermal Management Wearable Clothing

Thermal management wearable system refers to the use of gases, liquids, phase change materials, and other cooling media for temperature control of the microenvironment under the clothing, to mitigate the heat stress of the human body in a hot environment [14]. There are various classifications of thermal management wearable systems based on different characteristics. First, according to the classification based on the cooling coverage, they can be divided into full-body-cooling garments [15] and localized-cooling garments [16]. Secondly, according to the classification of whether energy is consumed in the cooling process, it can be divided into active-cooling garments [17] and passive-cooling garments [18]. In addition, according to the classification based on the cooling medium used for cooling, it can be classified into evaporative-cooling clothing [19], air-cooling clothing [20], liquid-cooling clothing [21], phase change-cooling clothing [14], radiant-cooling clothing [18], and hybrid-cooling clothing [22]. Finally, the heat transfer pathways can be categorized as thermal convection, thermal conduction, and thermal radiation [6]. In the following part of this paper, we introduce and characterize the thermal management wearable system according to heat transfer pathways.

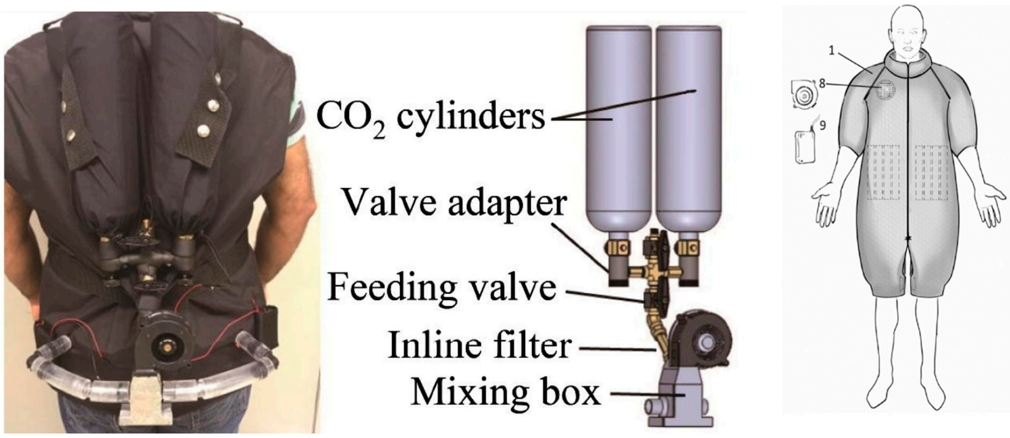
### *3.1. Thermal Convection Wearable Clothing*

Thermal convection wearable clothing is a type of clothing specifically designed to regulate the body's temperature. It is based on the principle that heat generated by the body is carried away by means of convection heat transfer to reduce body temperature or maintain a comfortable temperature. Gas-cooled garments and liquid-cooled garments are two common types of thermal-convection wearable clothing.

(1) Air-cooling clothing

Air-cooling clothing typically employs low-temperature compressed air or ambient air as a cooling medium. This is achieved by circulating the air through pipelines or a sandwich of clothing, which then comes into contact with the surface of the human body. The resulting convection heat transfer and evaporation then help to dissipate heat away from the body [20]. Air-cooling clothing can be classified into two types: duct-type air-cooling clothing and fan-type air-cooling clothing, as depicted in Figure 5. Sayed et al. proposed an air/$CO_2$-cooling garment, which utilized a cylinder to store high-pressure gas, and the compressed gas expanded as it passed through the orifice, thereby cooling the human microenvironment, as shown in Figure 5a [23]. To assess the cooling efficiency of the clothing, a total of 19 male participants were part of an experimental procedure. Compressed air was provided to the air-cooling clothing to facilitate an efficient airflow to the body. The temperature of the air supplied was temperature-dependent for workplace comfort. Nevertheless, duct-type air-cooling clothing has drawbacks, including a high weight, noise, and a low reliability, hindering portable design implementation.

To meet the needs of certain industries that prioritize both comfort and portability, researchers have devised cooling clothing with tiny fans that can fit each individual perfectly [24]. Wang et al. developed an air-cooled suit of dry ice combined with ventilation that successfully stopped the mascot actor's core temperature from rising during the performance, as illustrated in Figure 5b [25]. Twelve healthy male volunteers took part in the research. There were no reports of heat-related illnesses, as well as pulmonary, esophageal, and cardiovascular diseases. The mean age, weight, height, body surface area, and body mass index (mean ± SD) were 21.3 ± 1.9 years, 65.3 ± 6.5 kg, 1.75 ± 0.04 m, 1.79 ± 0.09 $m^2$, and 21.3 ± 1.9 kg/$m^2$, respectively. The primary aim of cooling garments is to mitigate heat stress in the human body by fostering the flow of ambient air throughout the body for enhanced evaporative cooling and convective heat transfer, as noted in Ref. [21]. Nevertheless, in environments featuring high temperature and high humidity, where sweat accumulates on the body surface, air-cooling clothing's efficacy is significantly restricted, leading to discomfort and potential metabolic imbalances, as discussed in Ref. [26]. Therefore, it may be necessary to select alternative cooling equipment for environments with high temperature and humidity levels.




(a) (b)

**Figure 5.** (**a**) Duct-type air-cooling clothing [23]; (**b**) Fan-type hybrid dry ice and air-cooling clothing [25].

(2) Liquid-cooling clothing

The fundamental principle of liquid-cooling clothing is for the cryogenic liquid generated by the cold-source equipment to transfer heat with the human skin through the cooling tubing inside the clothing. This process lowers the body's surface temperature and alleviates the heat strain caused by high temperatures [14]. Unfortunately, there are numerous flaws in the current design of liquid-cooled clothing. First, many of the current liquid-cooling clothing's cooling units are complicated, with some employing compressors to cool the refrigerant, adding excess weight to the system and being inconvenient for personnel to carry [27]. Second, the majority of liquid-cooling clothing is tailored for specific environments, making them unsuitable for general workplaces [28]. Third, scholars have utilized metal materials to construct piped systems for liquid-cooling clothing [29]. Although metals offer excellent thermal conductivity, they tend to be rigid and uncomfortable to wear. These suits are categorized as thermoelectric and ice liquid-cooled depending on the type of cold source used [30].

The thermoelectric liquid-cooling clothing, illustrated in Figure 6a, comprises four main components: a cooling device, a cooling piping system, a micropump, and a basic garment [17]. The circulating cooling water in the thermoelectric suit absorbs body-generated heat through the piping, effectively lowering the body's surface temperature [31]. In this process, the temperature of the hot side rises, and this temperature rise negatively impacts the cooling performance of the semiconductor cooling plate. Based on their experiments, Zhang et al. [17] found that the cooling effect improved with the increasing flow rate under an optimal operating voltage. The cooling suit's average maximum temperature difference was 5.5–39.2 °C. Thermoelectric liquid-cooling clothing has certain limitations, including a low coefficient of performance (COP), a reduced efficiency in high-capacity applications, and wide temperature ranges [32].

The ice liquid-cooling clothing, illustrated in Figure 6b, is typically worn with a fanny pack or backpack containing an ice bag. The coolant exchanges heat with the ice storage container, and a micropump propels the coolant through a circulating pipeline within the clothing to exchange heat with the human body [30]. This sort of liquid-cooled attire diminishes the device's intricacy, reduces cost, and enhances portability. As a result, it is more favored in the market and possesses greater practical application value. Nevertheless, liquid-cooling clothing necessitates the timely replacement of its cooling source. For a liquid-cooling suit, it is necessary to configure the type of cooling medium, inlet temperature, and flow rate according to the actual situation. Table 1 shows the type of medium, medium temperature, medium flow rate, and cooling efficiency for liquid-cooling clothing.

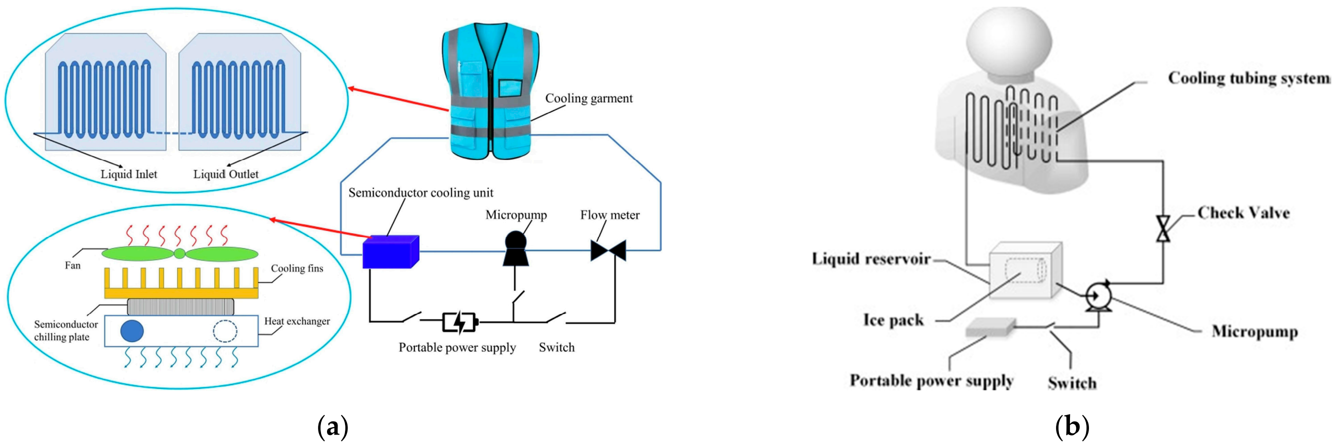



**Figure 6.** (**a**) Thermoelectric liquid-cooling clothing [17]; (**b**) ice liquid-cooling clothing [30].

**Table 1.** Cooling medium parameters and cooling efficiency.

| References | Environmental Temperature | Environmental Humidity/% | Liquid Temperature/°C | Liquid Flow Rate/L·min$^{-1}$ | Cooling Efficiency/W |
|---|---|---|---|---|---|
| [21] | 30 °C | 40 | - | 3.8 | 300 |
| [17] | 39.2 °C | 60 | 16 | 0.9 | 160.43 |
| [33] | 30 °C | - | 15.7 | - | 340.4 |
| [34] | 45 °C | - | - | 0.54 | 243.2 |
| [25] | 34.0 ± 0.5 °C | 78 ± 5 | 5.3 | 0.5 | 169.2 |
| [35] | 35 °C | 60 | 22 | - | 210 |

### *3.2. Thermal Transfer Wearable Clothing*

Thermal transfer wearable clothing is a specialized garment that removes heat generated by the body through heat transfer, regulating body temperature. A prevalent type of heat transfer wearable clothing is the phase change-cooling suit. This cooling utilizes phase-change materials (PCMs) that absorb a considerable amount of latent heat at the phase-change point, resulting in cooling the human body. PCMs are a significant energy storage option [36,37], categorized into three groups: organic materials, inorganic materials, and mixed cocrystals of the two [38]. Specific features are presented in Table 2 [39]. The phase-change cooling suits usually have pockets on the front and back that are specifically designed for the PCMs. Before usage, the materials should be stored in a cold environment to preserve their coldness, and they are later placed in the pockets. Once the PCM absorbs heat and undergoes a phase change, it is taken out and placed back in a cold environment to store cold for the next usage [40]. The cooling effectiveness of the phase-change cooling suit is determined by the specific phase-change material used. Different materials extract varying degrees of heat during the phase-change process, resulting in differences in cooling capacity. The cooling duration of the suit typically lasts between 2 and 5 h [41]. Refer to Figure 7 for a schematic illustration of the phase-change cooling suit's structure [3].

**Table 2.** Comparison of different phase-change materials.

| Description | Organic PCMs | | Inorganic PCMs | | Eutectic Material |
|---|---|---|---|---|---|
| Materials | Fatty acids | Paraffinic | Metals | Hydrated salt | Mixtures |
| Melting point | 30~70 °C | 40~70 °C | 20~100 °C | −20~100 °C | −20~100 °C |
| Latent heat | 150~250 kJ/kg | 150~250 kJ/kg | 100~500 kJ/kg | 200~400 kJ/kg | 100~500 kJ/kg |
| Advantages | Good stability, good reusability, well-defined phase-transition point [42] | Good stability, good reusability, adjustable melting point [43] | Good stability, good thermal conductivity, nontoxic and harmless [44] | High latent heat, good reusability, inexpensive [45] | High thermal conductivity, high latent heat, good stability, adjustable melting point [46] |
| Drawbacks | Low melting point, low phase-transition temperature range, easily contaminated, toxic, and slightly corrosive | Corrosive to plastic containers. High volume change, volatile, flammable | High melting point, high weight, small phase-transition temperature range, more expensive | Corrosive and slightly toxic. Poor stability, susceptible to moisture, easily crystallized | Heavy weight and high cost |

**Figure 7.** Phase-change cooling clothing [3].

Phase-change cooling clothing has a simple structural design, does not require the installation of refrigeration equipment like air-cooled suits and liquid-cooled suits, is easy to put on and take off, and has a good cooling effect. However, the production cost of phase-change materials is high, the weight of phase-change materials increases the burden of the cooling suit, and the phase-change materials installed in the pockets of the clothing lead to phase-change cooling suits with poor breathability, preventing the evaporation of sweat. To improve the cooling performance of phase-change cooling clothing, the common method is to select phase-change materials with high thermal properties and temperatures close to the skin temperature and reasonably distribute phase-change materials according to the temperatures of different parts of the human body. In addition, adding an insulating layer outside the phase-change material to reduce the heat absorption of the phase-change material from the external environment, and adding metal nanoparticles, graphene, or other thermal fillers to the phase-change material to enhance the thermal conductivity of the phase-change material is also one of the methods to improve the cooling performance of phase-change cooling suits [14]. Tesar and Kordik [47,48] conducted experimental tests on PCM-based clothing for soldiers in hot desert climates. The moderate melting-point temperature of n-ecosane (35.7 °C) made it highly advantageous as it allowed for the maintenance of a temperature of 35 °C. Butts et al. [49] utilized PCM to cool 20 male participants in their clothing and observed a significant reduction in their thermal, psychological, and perceptual strains when compared to males not exposed to PCM under test conditions of 34.2 °C and 54.7% RH.

### 3.3. Thermal Radiation Wearable Clothing

The utilization of radiative cooling in thermal protective clothing exhibits potential for energy conservation owing to its passive nature. Human skin displays emissivity values greater than 0.95 [50,51] and can be regarded as being almost entirely comprised of blackbody radiation. This elevated emissivity characterizes the human skin as a special infrared emitter. In a typical indoor setting, up to 50% of the total heat loss arises from radiation [52]. Nevertheless, traditional clothing design does not make provisions for the radiation component. Radiant cooling clothing is a developing approach to cooling the body. It achieves this by enhancing the body's radiative heat loss to the environment, as well as reflecting heat radiation from sunlight through the spectral selectivity of the fabric's microfiber structure [53]. The use of passive cooling technology in radiant cooling suits means that they do not require an external energy supply, bringing the benefits of simplicity and energy savings. Since the solar spectrum is mainly between 0.3 and 4.0 µm [53], it is promising and feasible to enhance solar reflection and dissipate human thermal radiation. Zhao et al. developed a layered nanofiber textile with improved thermal insulation and radiant heat management for effective personal heat management in harsh temperatures, achieving a temperature reduction of 7.2 °C over white cotton in hot environments, as shown in Figure 8 [54].

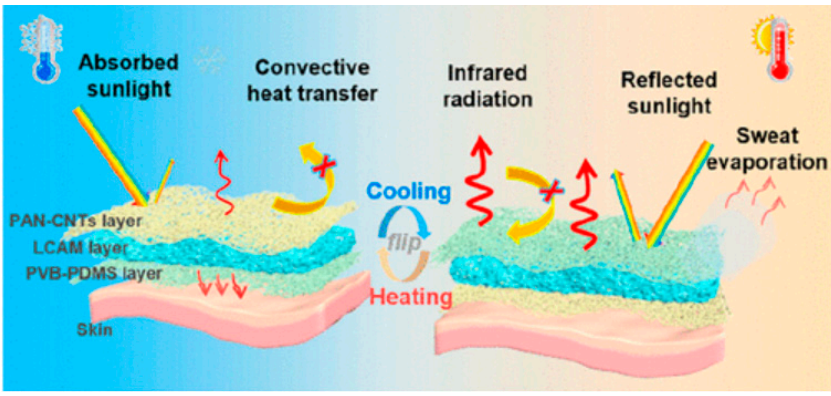



**Figure 8.** Thermal-radiation cooling clothing [54].

In recent years, numerous research teams have focused on creating textiles that possess exceptional radiative cooling capabilities. Cai et al. [53] were the first to present a spectrally selective, radiatively cooled textile suited for outdoor cooling, with an over 90% reflectance of solar irradiance and a satisfactory transmission of thermal radiation to the human body. This was achieved through avoiding overheating of the simulated skin, ranging from 5–13 °C when compared with cotton fabrics. Irfan et al. [55] developed a nanotextile using nanoparticle-doped polymeric materials and electrostatic spinning technology. Results showed 91% solar reflectance, 81% mid-infrared transmission, and a cooling performance of 9 °C compared to cotton textiles.

These findings suggest that radiatively cooled clothing has great potential for effective cooling and various applications. In addition, a thorough examination of radiant thermal cooling and heating, which includes reflective surfaces, has been conducted [56]. This review offers significant insights into radiant-cooling technologies. Radiant-cooling technology has a critical role in personal thermal management, particularly in the context of clean energy radiation that does not contribute to carbon emissions. However, this technique is limited by weather conditions and cannot be fully applied in all circumstances [57]. Lin et al. [58] conducted a comprehensive review study addressing atmospheric conditions in various regions, including application challenges. Nonetheless, many issues still need to be addressed for passive personal cooling clothing, such as material stability, durability, and comfort. Thus, there are currently no established products available for practical use. Therefore, extensive research and development are required to enhance the effectiveness and dependability of novel radiative cooling materials and manufacturing techniques. Table 3 presents an outline of thermoregulation textiles that rely on radiant heat transfer.

**Table 3.** Summary of thermoregulation textiles based on thermal radiation.

| References | Types | Materials | Results |
|---|---|---|---|
| [51] | Radiation-cooled, infrared, transparent, visible, opaque fabric | Parallel-aligned polyethylene fibers with a low infrared absorbance | The infrared transmittance of the fiber is 0.972 |
| [59] | Radiation-cooled fabrics are opaque, transparent to mid-infrared | Nanoporous polyethylene | It reduces skin temperature by up to 2.7 °C. |
| [60] | Radiation-cooled fabrics are opaque, transparent to mid-infrared | Homogeneous and continuous nano-polyethylene | It reduces skin temperature by up to 2.3 °C. |
| [61] | Cooling and heating of fabrics by mid-infrared emitted radiation | Polyethylene nanolayer | Maximum core temperature reduction up to 36.59 °C |
| [62] | Mid-infrared solar reflective emission cooling textiles | Integrated solar reflectors and thermal emitters | 5 °C cooling in direct sunlight |
| [63] | Mid-infrared solar reflective emission radiation heating and cooling of textiles | Photonic structure | Temperature difference of 20 °C for radiant textiles |
| [64] | Low and medium infrared-emitting radiant fabrics | Silver nanowire composite coated on cotton | Average reflectivity is 66% higher than conventional fabrics |

### *3.4. Hybrid-Cooling Wearable Clothing*

Hybrid-cooling wearable clothing refers to garments that employ a combination of two or three heat-transfer mechanisms [65].

Hybrid-cooling wearable clothing is specifically engineered to optimize the benefits of various cooling techniques to achieve a superior cooling efficiency [22]. Figure 9 demonstrates a hybrid-cooling wearable clothing that combines microfans and PCM to improve cooling efficiency while addressing the drawbacks of air-cooling and phase change-cooling clothing [66]. Wang et al. [25] designed a suit based on dry ice and ventilated fans, utilizing the sublimation of dry ice to reduce the wearer's load and reinforce air circulation to effectively alleviate thermal discomfort in mascot actors. The experiment demonstrated the effectiveness of the hybrid-cooling suit in preventing the mascot actor's core body temperature from exceeding 38.0 °C and consistently maintaining an average skin temperature below 36.5 °C. Ni et al. [67] proposed a hybrid-cooling garment that combined PCM and a ventilation fan, resulting in the improved regulation of heart rate and skin temperature. One of the benefits of this design was that the PCM, without additional cooling, absorbed a significant amount of potential [37,68–70]. Kang et al. [71] provided a similar hybrid design that combined PCM and a ventilation fan, which was also proven effective in thermal management. The design of hybrid-cooling suits can be customized to different usage scenarios and necessities. For instance, in high-temperature environments, liquid and air cooling can be combined to take advantage of the effective cooling properties of liquid and the rapid cooling features of air, resulting in faster and more efficient cooling. In addition, hybrid-cooling wearable clothing could incorporate additional features, such as protection and breathability, to better meet user needs.

### *3.5. Characterization of Thermal Management Wearable Clothing*

Personal cooling clothing effectively lowers the body's surface temperature in high-temperature settings, reduces discomfort and fatigue caused by heat, improves work efficiency, and protects individuals' health. The suit finds practical uses in various settings such as industrial production, fieldwork, and others that require cooling. The performance characteristics of various cooling suits are compared in the introduction above. Please refer to Table 4 for a summary of the results.

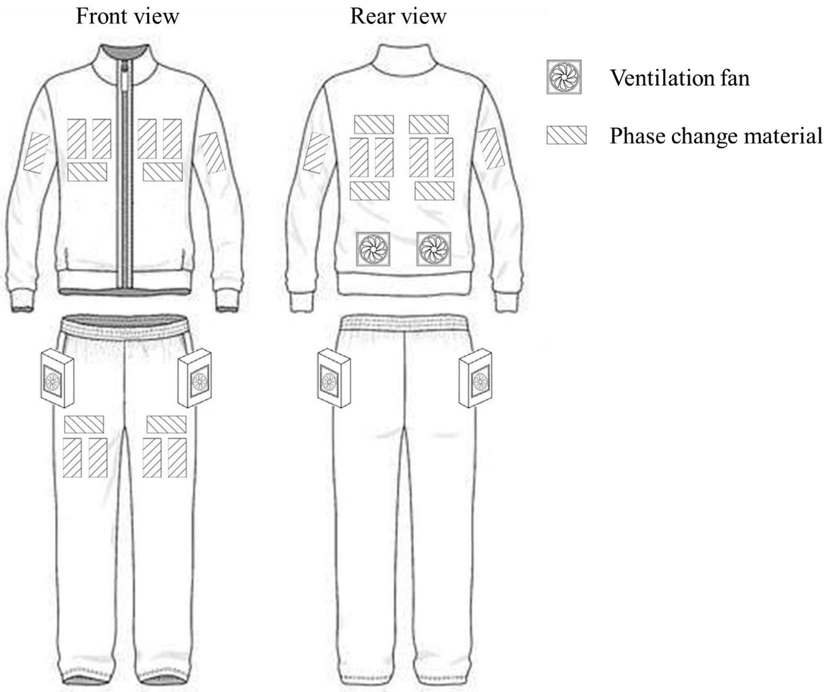



**Figure 9.** Hybrid-cooling wearable clothing [66].

**Table 4.** Comparison of performance characteristics of several cooling clothing [72].

| Types | Cooling Method | Total Weight | Cooling Temperature | Mean Cooling Power (6 h) | Notice |
|---|---|---|---|---|---|
| WCDS | Thermoelectric and blowers | 1.2 kg | 26.5∼28.8 °C | 51.7 W | - |
| Air-cooling clothing | Ventilating fans | 0.7 kg | 32.5 °C | 9 W | - |
| Liquid-cooling clothing | Ice water and water circulation tubing system | 4.3 kg | 11.1 °C | 37.1 W | Condensation water |
| Ice-cooling clothing | Ice gel packs | 1.9 kg | 4.2 °C | 25.6 W | Condensation water |

Note: -, not available.

In summary, although these cooling methods can effectively regulate the temperature of the environment around the human body to a more suitable temperature if the temperature of the cooling medium is lower than the dew point of the air, it will lead to the emergence of a condensation phenomenon. Condensation is the process by which water vapor on the surface or inside a cooling suit condenses into water droplets when it comes in contact with a cooler surface [73].

The occurrence of condensation is a challenge to human comfort. When condensation occurs, garments around the human body become wet, which not only causes discomfort but also leads to increased heat loss, further affecting the body's perceived temperature. Damp garments can also cause discomfort or health problems, such as a feeling of coldness and moisture that harbors bacteria [74]. As a result, cooling alone to reduce body temperature is no longer sufficient to meet the body's comfort needs.

There are a number of factors that need to be considered to address the problems associated with the risk of condensation. Firstly, the design of cooling suits should take full account of factors such as ambient temperature and humidity to determine the appropriate cooling water temperature and avoid the occurrence of condensation caused by cold water that is too low. Secondly, the material and structure of the cooling suit should have good moisture permeability and fast drying properties to quickly remove moisture and improve wear comfort [75].

## 4. Classification and Characteristics of Moisture Management Wearable Clothing

The quantity of sweat that does not evaporate from the skin's surface per hour is typically between 30 and 80 g when the surrounding temperature is not high. Under such circumstances, the sweat can easily spread into the surrounding environment through the gaps among clothing fibers. Yet, during physical exertion or hotter weather, sweat production significantly increases resulting in a larger quantity of sweat accumulating on the skin's surface [72]. At present, it is no longer sufficient for clothing to simply be breathable and permeable to moisture in order to effectively dissipate sweat. Rather, clothing must be able to absorb significant amounts of sweat before releasing the resulting moisture into the surrounding air through evaporation. In cases where the surrounding air is dry or windy, sweat can evaporate quickly. However, if the humidity of the surroundings exceeds 60%, individuals may feel increasingly uncomfortable. Therefore, being in a highly humid environment or sweating during exercise and causing your clothing to become wet can influence and alter the thermal and humidity comfort of your attire.

Personal moisture management wearable clothing is a type of clothing with a unique design that is capable of effective sweat regulation in addition to body temperature regulation. Moisture transport in textiles has a significant impact on the physiological comfort of the human body. When the human body produces sweat, a series of wetting, penetration, transport, and evaporation processes occur with the textile. At the same time, the temperature, humidity, and wind speed of the environment will also have an impact on the exchange of moisture and heat, which further affects the comfort of the human body.

### *4.1. Moisture Management Materials*

Textile regulation of humidity is the process of transferring perspiration through the textile and usually involves two aspects depending on the different aggregation states of humidity, i.e., the regulation of sweat vapor and liquid sweat [76]: (1) the movement of moisture in the gaseous components of the material, e.g., the transfer of water molecules within fibers or in the space between fibers; (2) the interaction of humidity with the solid components of the material, e.g., repulsion or adsorption of water molecules with hydrophobic or hydrophilic groups for humidity transfer.

(1) Water vapor regulation

Gaseous perspiration wearable clothing is an important sweat transfer method in wet management wearable systems. Evaporative-cooling garments are used to remove heat from the body by absorbing heat through the evaporation of moisture as shown in Figure 10 [19]. Evaporative-cooling garments can be made from a variety of highly absorbent polymers that are more effective than conventional textiles [77–80]. When the human body perspires, the sweat penetrates the inner fabric layers of the moisture management garment. These inner fabric layers are usually made of special materials that have a large surface area and good breathability. Through the action of this material, sweat can evaporate quickly, removing heat from the body's surface and expelling moisture from the body. In this way, individual moisture-regulating clothing can help the human body stay dry and comfortable, avoiding excessive sweat accumulation on the skin surface, which causes discomfort and a feeling of wetness and coldness [6]. At this point, water vapor moves through the air space between fibers by diffusion or through their internal molecular structure when the vapor is under a vapor concentration gradient. Current sweat vapor-conditioning methods generally involve the design of materials that facilitate the transfer of sweat vapor from the body to the environment, which is achieved through pore size design, i.e., materials with a high water vapor permeability [81].

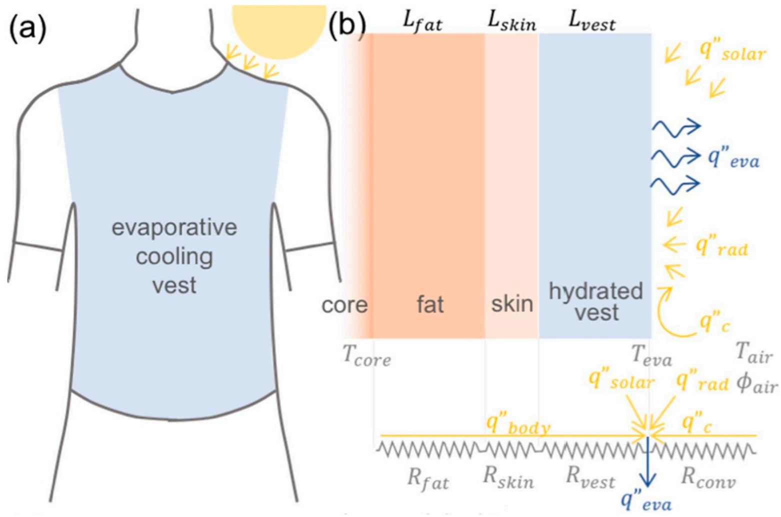



**Figure 10.** (**a**) Schematic diagram of evaporative cooling clothing; (**b**) heat and mass transfer processes involved in evaporative cooling [19].

The evaporative moisture-regulating clothing material has strong water absorption properties and good breathability and comfort, which can effectively help sweat to be discharged, thus enhancing the effect of evaporative cooling [79]. It is worth noting that the effect of evaporative-cooling clothing is greatly affected by environmental factors, and in high-temperature and high-humidity environments, it is difficult to evaporate the moisture inside the clothing, so the effect of evaporative cooling will be limited. On the contrary, in an environment with a low relative humidity, the effect of evaporative cooling will be better because the moisture is easier to evaporate, thus removing body heat [82]. Therefore, the advantages of evaporative-cooling garments are that they are light to wear, easy to use, simple to manufacture, and suitable for industrial mass production; the disadvantages are that the liquid adhering to the inner surface of the garment seriously affects the comfort of the human body, inhibits the evaporation of sweat, and is more effective in environments with a low relative humidity.

(2) Liquid vapor regulation

As an intermediate layer between the skin and the environment, textiles play a critical role in achieving personal comfort and safety by managing the thermal and moisture conditions of the localized body. When liquid sweat is in direct contact with the moisture-regulating clothing material, liquid sweat is transferred through the material in both in-plane and trans-plane directions [83]. Many studies have focused on sweat-directed transplanar transfer, i.e., the transfer of liquid sweat from the skin to the outer surface of the material to keep the skin dry. Many researchers have achieved a directional liquid transfer of materials through a fabric structure design by mimicking plant structures [84]. Miao et al. investigated sandwich-structured textiles with hierarchical nanofiber networks and Janus wettability, as shown in Figure 11 [85]. The human body temperature covered by this sandwich-structured textile decreased by about 4.2 °C with rapid sweat evaporation compared to commercial cotton textiles. The driving force for the movement of liquid sweat within the material was capillary forces, which were influenced by intermolecular forces between the liquid and the surrounding fiber surfaces, as well as the size and configuration of the space within the textile. Although water transfer in materials is accompanied by energy transfer, existing material strategies have paid less attention to the energy transfer of liquid sweat. Most material designs for liquid sweat conditioning do not quantify or consider the thermal energy transfer involved [86]. As shown in Figure 11, sweat can affect cooling efficiency in two ways: (I) by increasing the evaporative distance from the skin through cross-plane transfer and (II) by increasing the evaporative surface area through in-plane transfer.

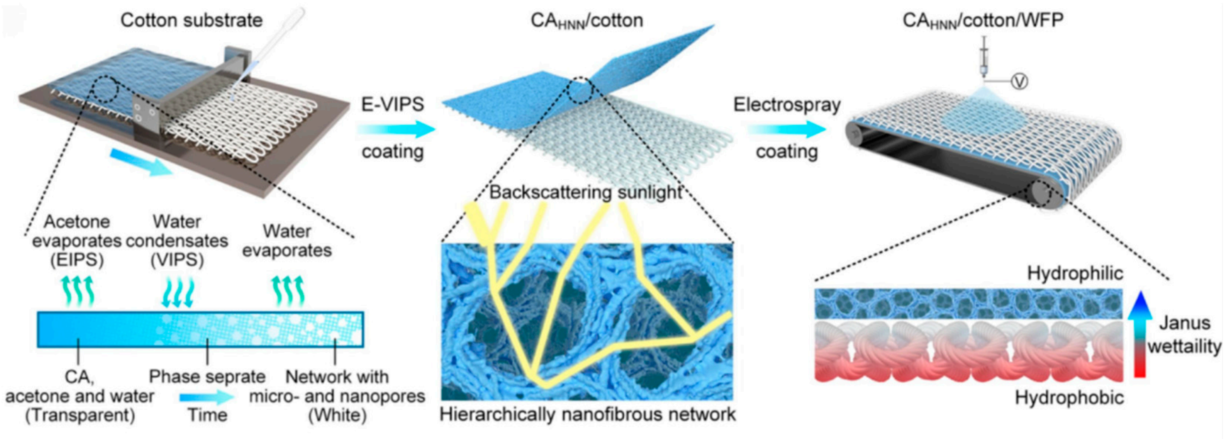
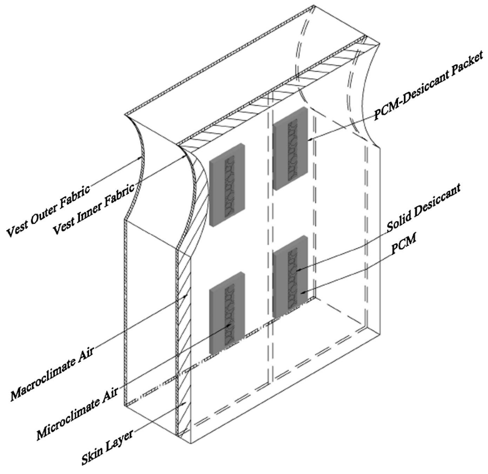



**Figure 11.** Schematic representation of textiles with hierarchical nanofiber networks and Jannus wettability [85].

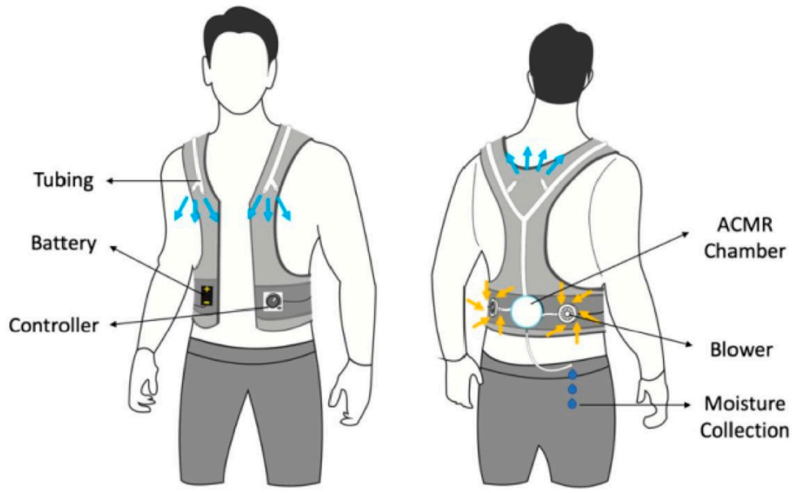
*4.2. Moisture Management Clothing*

The effectiveness of thermoregulatory clothing is limited in hot and humid environments because less moisture is transferred to the pairs within the garment, with the attendant risk of sweating and condensation within the thermoregulatory clothing. Wang and Hu [87] showed that the average thermal sensation in humans under hot conditions was related to the sensation of sweating. Keeping the skin and microclimate air dry can be achieved by using solid desiccant packs. Solid desiccants such as silica gel can reduce the moisture content of the microclimate air between the fabric layers within the cooling undershirt through an adsorption process. However, the released adsorbed heat can increase the temperature of the microclimate air if the thermoregulation suit is not sufficient to absorb the heat generated by the desiccant and lost from the human torso [88]. It is of interest to determine whether a thermoregulation device in combination with a desiccant pack would improve the cooling performance of the undershirt.

The purpose of the PCM composite desiccant packs proposed by Mariam Itani et al. [89] was to provide cooling to the human body working in hot conditions and to adsorb water vapor in the microclimate air, thus increasing the evaporation of sweat from the skin layer and improving the cooling of the human body. Experimental modeling and validation were conducted to find the state of the microclimate air and its moisture content under the influence of using PCM desiccant packs. The idea was to use a solid desiccant in addition to the PCM package to keep the skin and the macroclimatic air layer dry to prevent condensation and enhance sweat evaporation from the skin, as in Figure 12a [89]. A wearable cooling and dehumidification system was designed by Lou et al., as shown in Figure 12b [72]. A lightweight air-ventilated undershirt was worn underneath a protective suit, and an air cooling and moisture-removal (ACMR) chamber was attached to the lower back area of the knitted undershirt. In a simulated hospital environment, the optimal cooling effect corresponded to a 3.5 °C drop in ambient temperature and a 6% reduction in relative humidity. The properties of sweat-expulsion clothing and desiccant-adsorption wearable clothing are demonstrated in Table 5. Specific properties may vary depending on product design and material selection. When selecting an appropriate moisture management garment, it is recommended that a comprehensive evaluation be performed based on individual needs and environmental conditions.




(a)




(b)

**Figure 12.** Schematic diagram of (**a**) PCM composite desiccant packages [89] and (**b**) ACMR for clothing [72].

**Table 5.** Comparison of sweat expulsion clothing and desiccant adsorption wearable clothing.

| Types | Principle | Dehumidification Effect | Drawback |
|---|---|---|---|
| Moisture management materials | Surface evaporation | 140–160 g/m$^2$/h [74] | Depending on ambient humidity |
| Desiccant-dehumidification clothing | The adsorption capacity of the desiccant | Decrease from 21.23 g/kg to 19.74 g/kg [89] | Dehumidification process is exothermic |
| Condensation-dehumidification clothing | Cold-surface condensation | 26.3 g/h [72] | High energy consumption, condensation |

In summary, there is a risk of temperature increase in dehumidified clothes during the process of humidity regulation, especially when desiccant-dehumidified clothes use a desiccant to absorb water vapor around the human body. However, this method of dehumidification can effectively regulate the humidity of the environment around the human body to keep it appropriate. However, at the same time, the absorption of water vapor releases latent heat, which causes the temperature of the desiccant to increase [89]. This phenomenon of temperature increase has a certain impact on human comfort. As the temperature of the desiccant increases, the temperature of the garment around the human body increases accordingly, reducing comfort. As a result, dehumidification alone can no longer satisfy the human body's need for comfort. Despite the rapid development of materials, there are both challenges and opportunities. Can new textiles maintain all aspects of their performance after many normal washings? Consideration should also be given to whether the materials are sufficiently readily available and cost-effective for large-scale industrial production.

A number of factors need to be considered to address the problems associated with rising temperatures. First, the design of dehumidifying garments should take full account of the thermal conductivity and heat dissipation properties of the desiccant to minimize the extent of a temperature rise. Secondly, the material and structure of the dehumidifying garment should have good air permeability and heat dissipation to quickly dissipate heat and maintain a suitable temperature on the surface of the garment. In addition, the use of intelligent control systems can monitor and regulate the dehumidification process to ensure a balance between dehumidification performance and comfort.

## 5. Performance Evaluation Indicators of Personal Wearable Thermal and Moisture Management Clothing

At present, there are many methods for evaluating the thermal and moisture comfort of garments, mainly analyzing and evaluating them from physical [90], physiological [91], and psychological [65] perspectives, and the evaluation methods can be divided into subjective and objective evaluations. An objective evaluation uses physical indicators and their fabric performance indicators and human physiological indicators, and a subjective evaluation is based on the psychological indicators of the human body [92–94].

### *5.1. Objective Evaluation Methods*

The objective evaluation method is an evaluation method that uses objectively changing data that can be specifically measured and the results derived by instruments [94]. This evaluation method mainly evaluates the thermal and moisture comfort of garments from the following aspects: (1) using the thermal and humidity properties of textile materials as well as the thermal and humidity properties of the entire garment to evaluate the thermal and humidity comfort of the garment [95]; (2) using the garment microenvironment as the basis for the study of thermal and humidity comfort, and reflecting the influence of fabrics on the human body's sense of comfort by measuring the changes in temperature and humidity of the climatic region between the fabric and the skin, and proposing evaluation indices [96]; (3) analyzing human physiological data, clothing physiology points out some important physiological indexes, including body core temperature [97], average skin temperature [90], average body temperature, metabolic heat production, heat balance difference, heat loss, perspiration, heart rate [98], and blood pressure [99,100].

Typically, a two-step method is used for active sweat measurement. The measurement process of this method is as follows: first, the dry heat dissipation is measured while wearing a thousand dummy garments, and then the total heat dissipation (including the evaporative heat dissipation portion) is measured for a wet dummy attire. By calculating the wet heat dissipation minus the dry heat dissipation, the result of evaporative heat dissipation can be obtained [101]. In contrast, the "Walter" sweat warmer dummy for passive sweating uses a different measurement method [102]. In the measurement process, the total moisture resistance is calculated by considering the skin as a layer of the garment, and then the moisture resistance of the skin is subtracted from the total moisture resistance to obtain the moisture resistance of the garment and the surface air layer. Different from the two-step method, the evaporated sweat and wet-state heat dissipation of the warm body dummy are measured first in the measurement process to get the wet resistance and thousand-state heat dissipation, and then the thermal resistance is calculated based on the dry-state heat dissipation. As an instrument for testing the overall thermal and humidity performance of garments, the warm body dummy can simulate the mass transfer and heat transfer between the human body and the environment. Its measurements are objective, accurate, and repeatable [103]. To avoid ethical issues, inter- and intrasubject variability, and high costs, sweat dummies are often used to simulate sweat-induced evaporative cooling. Table 6 shows the different sweating simulation methods dummies used [104].

**Table 6.** Dummies with different methods of sweating simulation.

| References | The Dummy | Characterization |
|---|---|---|
| [105] | Tore | Prewetted tight fabric skin applied to a dry thermal manikin |
| [102] | Walter | Water-filled manikin with a waterproof but vapor permeable surface |
| [104] | Coppelius | Manikin with an inner skin spreading water superficially and an outer vapor-permeable skin |
| [106] | Newton | Manikin with a supply of water to a fabric skin by means of sweating outlets distributed over the manikin's surface |
| [104] | ADAM | Manikin with a porous metal surface with superficial sweating |

### 5.2. Subjective Evaluation Methods

The subjective evaluation method is a method of measuring the thermal comfort of garments which utilizes the psychological thermal comfort feelings of subjects in a specific environment for the assessment and is also known as the psychological method. As a supplement and validation of the objective evaluation method, the steps of this method are to predesign a questionnaire form and allow subjects to rate the comfort indicators of the garment according to their personal psychological feelings during the garment-wearing experiment. The scales and the meaning of subjective votes are shown in Table 7. The determination of the indicators and the division of the scoring scale are the key links in the subjective evaluation method, which still needs to be further improved.

**Table 7.** Subjective rating scales.

| Scales | Thermal Sensation | Thermal Comfort | Thermal Satisfaction | Thermal Preference | Sweat Feeling | Cold Stimuli Sensation |
|---|---|---|---|---|---|---|
| +4 | Very hot | Extremely uncomfortable | Very unsatisfied | | | Very strong cold stimuli sensation |
| +3 | Hot | Very uncomfortable | Unsatisfied | Much warmer | The very strong feeling of sweating | Strong cold stimuli sensation |
| +2 | Warm | Uncomfortable | Slightly unsatisfied | Warmer | The strong feeling of sweating | Medium cold stimuli sensation |
| +1 | Slightly warm | Slightly uncomfortable | Satisfied | A little warmer | Slight feeling of sweating | A little cold stimuli sensation |
| 0 | Neutral | Comfortable | Very satisfied | No change | No feeling of sweating | No cold stimuli sensation |
| −1 | Slightly cool | | | A little cooler | | |
| −2 | Cool | | | Cooler | | |
| −3 | Cold | | | Much cooler | | |
| −4 | Very cold | | | | | |

The sweating dummy is also a tool for assessing the comfort of garments, effectively avoiding moral and physiological factors in human experimentation, and is not subject to psychiatric factors. It has a good reproducibility. However, the sweating dummy is still a device that simulates the shape and physiological characteristics of the human body, and its assessment results do not fully and realistically reflect the actual subjective feelings of humans.

### 5.3. Thermal and Moisture Regulation Model

The thermal and moisture regulation model is a method for evaluating the thermal and humidity comfort of garments, which simulates the processes of human body temperature regulation and thermal and moisture transfer of garments by establishing a thermal and moisture transfer model. The thermal and moisture regulation model has been widely used at home and abroad to evaluate the thermal and humidity comfort of clothing, which mainly includes the human body temperature regulation model, the thermal and moisture transfer model of clothing, and the human body–clothing–environment system model.

#### 5.3.1. Human Thermoregulation Model

The human thermoregulation model consists of equations describing heat transfer and regulatory responses in the body. Over the last half-century, scholars have conducted substantial research and developed numerous human thermoregulation models. These models differ in the delineation of body nodes, and different methods of delineating body nodes correspond to different forms of equations for describing the regulatory responses of the body [107,108].

(1) The two-node model

The simplest two-node model, in which the human body is represented by a segment with two nodes in the core and skin layers, has gained popularity in engineering applications due to its simplicity, ease of implementation in computer tools, and faster computation time [109].

Gagge et al. laid the foundation for a two-node model of the whole body. The model was based on a direct, one-dimensional, transient heat transfer from the core to the skin layer to the environment. However, the thermoregulatory systems of sweating, skin blood flow, and shivering were based on empirical relationships developed for the average young adult. The accuracy of empirical models, especially the model constants, is closely related to experimental conditions, parameter ranges, quality of measurements, and physiological differences in subjects [110]. Doherty et al. [111] found that the model underpredicted skin wettability by 0.16 °C, and core temperature by 0.31 °C, but overpredicted skin temperature by 0.48 °C. At the same time, Ooka et al. [112] found that the model predicted a skin temperature 0.75 °C higher and a core temperature 0.32 °C lower. The model deviated from the experimental results. In addition to this, Takada et al. [107] found that the model underestimated skin temperature by up to 1.8 °C and core temperature by up to 0.5 °C, under cold-exposure conditions. Therefore, further improvement of the thermoregulatory system of the two-node model is needed, and a corresponding improvement scheme should be proposed. The flow diagram of a two-node model of the thermoregulatory system is shown in Figure 13 [113]. In this system dynamics model, the core and skin nodes of the Gagge model are modeled as two stocks that store the body's energy, which is then converted into the temperatures of two nodes, $T_{\text{skin}}$ and $T_{\text{core}}$.

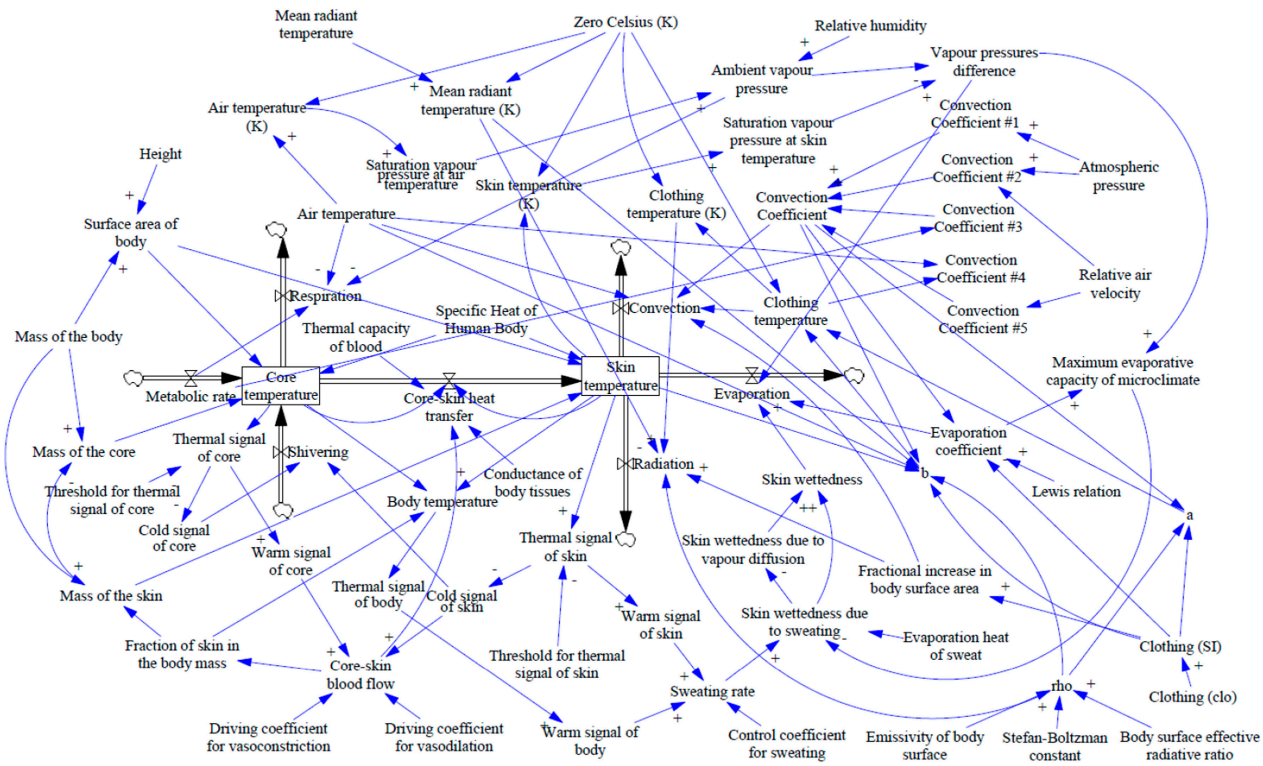



**Figure 13.** Flow diagram of a two−node model of the thermoregulatory system [113].

To overcome this problem, recent studies have proposed improved two-node models to more accurately assess the effects of personal cooling systems. These improvements include the consideration of local insulation and heat transfer in clothing, as well as modeling the heat exchange characteristics of cooling devices [114].

(2) Multinode model

The multinode body heat model is an extended and more complex version of the two-node model, as shown in Figure 14 [115]. Various models have been proposed to predict the state of heat regulation in the human body. Perhaps the most influential is the 25-node model proposed by Stolwijk [116], consisting of 24 body "nodes" (six body segments with four compartments each) and a central blood "node". Each node has a certain amount of metabolic heat generation, convective heat exchange with the central blood chamber, and convective heat exchange with neighboring nodes. Subsequently, some scholars have also improved this human thermal regulation model to make it suitable for application in a wider range of scenarios, such as cold environments, space environments, and so on. Researchers have made various enhancements to the model to accurately forecast the patterns of local responses in different parts of the human body. Munir et al. [117] reassessed the dynamic characteristics of the Stolwijk model and examined several modifications to the model.

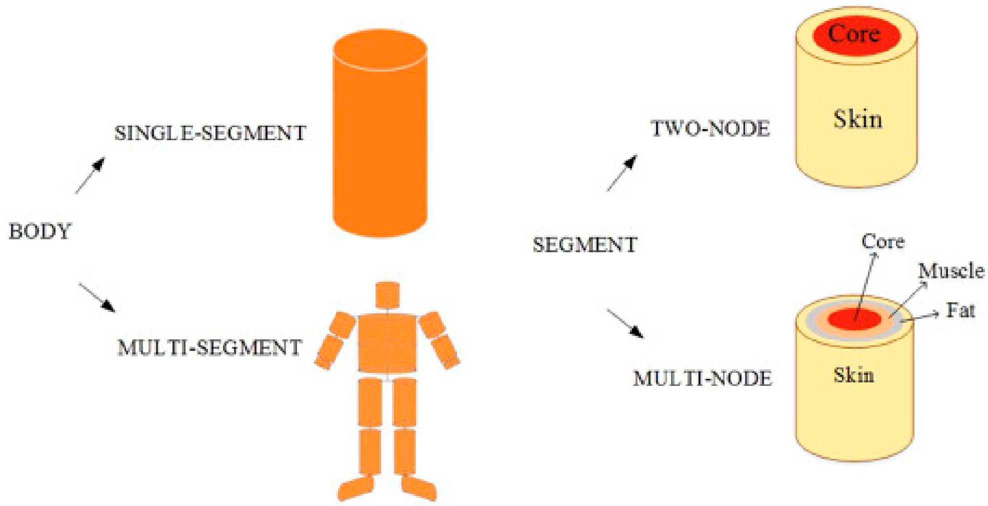



**Figure 14.** Comparison of the model segmentation, and the two-node and multinode models [115].

Multinodal models use partial differential equations to describe the heat transfer problem in the human body. The differential equations are usually discretized using the finite difference method, finite volume method, or finite element method to obtain the linear algebraic equations at each node. The advantage of the multinode model is that it can be divided into sections and nodes as needed, has better flexibility and accuracy, and can be applied to dynamic, nonstationary environments. The disadvantage is that the accuracy is not as good as the multinodal model in environments with large temperature gradient changes. The characteristics of the specific model can be seen in Table 8.

**Table 8.** The characteristic of the specific models [114,118].

| Model Name | Model Classification | Model Characteristics |
|---|---|---|
| Human thermoregulation model | Two-node model<br>Multinode model | When there are large temperature differences in the human body, more accurate simulation results can be obtained by using multinode and multiunit models. |
| Heat and moisture transfer modeling of clothing | Steady-state model<br>Transient model | Simulate the heat and moisture transfer process of garments to derive the heat and moisture properties of garments. |
| Human body–clothing–environment system model | - | The human body–clothing environment as a whole combines a model of human thermoregulation and a model of heat and moisture transfer from clothing. |

### 5.3.2. Evaluation of Thermal and Moisture Management Performance

There is no generalized performance evaluation method that can be used to assess the performance of wearable systems in managing thermal and moisture. The performance assessment of wearable systems involves two main aspects: (i) wearer comfort and safety; (ii) functionality of the wearable system. Ismail et al. [119] investigated the effect of uniform crosswinds on ventilation, heat, and moisture transfer to a clothed human body by simplifying the human body as a vertical cylinder with a uniform annular air layer. However, the existing evaluation methods are not sufficiently developed, especially for the performance evaluation of wearable systems under specific hot and humid conditions. Due to the wide variety of wearable systems and the different functions and technologies involved, specific assessment methods need to be developed for different types of wearable systems. These evaluation methods should be able to comprehensively consider the impact of thermal and moisture on the comfort and safety of wearable systems and accurately assess the performance of thermal and moisture regulation and energy conversion. Existing standard evaluation methods for thermal and moisture management of wearable systems are shown in Table 9 [75].

**Table 9.** Existing standard evaluation methods for thermal and moisture management of wearable systems.

| Thermal/Moisture Transfer | Thermal/Moisture Transfer | Indexes | Test Equipment |
|---|---|---|---|
| Human body → environment | Heat transfer | Thermal resistance | Hot plate; thermal torso; thermal manikin |
| | Moisture transfer | Liquid-water transfer indexes | Moisture management tester |
| | Coupled heat and moisture transfer | Evaporative resistance | Sweating hot plate; sweating torso; sweating thermal manikin |
| | | Water vapor transmission | Test dish, balance |
| Environment → human body | Heat transfer | Absorbed thermal energy | Thermal protective performance; tester, radiant protective performance tester |

From the perspective of thermal and moisture management, the performance evaluation of wearable systems can include the following aspects: (i) wearable comfort and safety under specific thermal and moisture conditions, taking into account the thermal and moisture regulation performance as well as the thermal and moisture conditions of the human body and the environment; (ii) wearable functionality under specific thermal and moisture conditions, including thermal and moisture energy conversion and physiological sensing. In order to evaluate the performance of wearable systems under such hot and humid conditions, there is a need to provide standardized and repeatable evaluation methods to support the development of wearable systems.

Our research group is currently developing a cooling and dehumidifying garment that uses membrane separation to reduce skin temperature and absorb surface sweat, thereby creating a cool and comfortable microenvironment within the garment. Therefore, future research should further explore technologies that simultaneously regulate temperature and humidity to improve thermal and moisture comfort for the human body and provide better protection.

## 6. Conclusions

The presented analysis provided a comprehensive overview of wearable systems for personal thermal and moisture management, discussing their functions, latest developments, and performance evaluation approaches. The findings contribute to the understanding of the challenges and considerations involved in regulating temperature and humidity within wearable systems. In the light of this study, the main findings derived can be stated as follows:

(1) Although current cooling methods are effective in regulating the surrounding temperature, condensation can result if the temperature of the cooling medium is below the dew point of the air.
(2) Moisture removal from textiles is strongly influenced by the humidity of the surrounding environment. In addition, when a desiccant is used to absorb water vapor from around the body, the desiccant absorbs the water vapor, releasing latent heat and leading to an increase in body temperature.
(3) Temperature and humidity regulation is a complex coupled process, and there are no generalized performance evaluation methods available to assess the performance of wearable systems in managing temperature and moisture.
(4) Addressing the issues involved requires considering a combination of cooling and dehumidification factors, such as the use of intelligent control systems, which play a vital role in maintaining the delicate balance between effective dehumidification performance and optimal comfort.

**Funding:** The research work presented in this article was financially supported by the Postgraduate Research & Practice Innovation Program of Jiangsu Province (No. SJCX23_0493).

**Data Availability Statement:** Further inquiries can be directed to the corresponding authors.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References


1. Song, G.; Wang, F. *Firefighters' Clothing and Equipment: Performance, Protection, and Comfort*; CRC Press: Boca Raton, FL, USA, 2019; pp. 217–268.
2. Kjellstrom, T.; Kovats, R.S.; Lloyd, S.J.; Holt, T.; Tol, R.S.J. The Direct Impact of Climate Change on Regional Labor Productivity. *Arch. Environ. Occup. Health* **2009**, *64*, 217–227. [CrossRef] [PubMed]
3. Wang, H.; Xu, Z.; Ge, B.; Li, J. Experimental Study on a Phase Change Cooling Garment to Improve Thermal Comfort of Factory Workers. *Build. Environ.* **2023**, *227*, 109819. [CrossRef]
4. Wu, G.; Liu, H.; Wu, S.; Liu, Z.; Mi, L.; Gao, L. A Study on the Capacity of a Ventilation Cooling Vest with Pressurized Air in Hot and Humid Environments. *Int. J. Ind. Ergon.* **2021**, *83*, 103106. [CrossRef]
5. Peng, Y.; Cui, Y. Advanced Textiles for Personal Thermal Management and Energy. *Joule* **2020**, *4*, 724–742. [CrossRef]
6. Sajjad, U.; Hamid, K.; Tauseef-ur-Rehman; Sultan, M.; Abbas, N.; Ali, H.M.; Imran, M.; Muneeshwaran, M.; Chang, J.-Y.; Wang, C.C. Personal Thermal Management—A Review on Strategies, Progress, and Prospects. *Int. Commun. Heat Mass Transf.* **2022**, *130*, 105739. [CrossRef]
7. Su, Y.; Tian, M.; Li, J.; Zhang, X.; Zhao, P. Numerical Study of Heat and Moisture Transfer in Thermal Protective Clothing against a Coupled Thermal Hazardous Environment. *Int. J. Heat Mass Transf.* **2022**, *194*, 122989. [CrossRef]
8. Hu, B.; Shi, X.-L.; Zou, J.; Chen, Z.-G. Thermoelectrics for Medical Applications: Progress, Challenges, and Perspectives. *Chem. Eng. J.* **2022**, *437*, 135268. [CrossRef]
9. Zhang, Q.; Wang, S.; Wang, X.; Jiang, Y.; Li, J.; Xu, W.; Zhu, B.; Zhu, J. Recent Progress in Daytime Radiative Cooling: Advanced Material Designs and Applications. *Small Methods* **2022**, *6*, 2101379. [CrossRef]
10. Wu, Q.; Liu, J.; Zhang, L.; Zhang, J.; Jiang, L. Effect of Temperature and Clothing Thermal Resistance on Human Sweat at Low Activity Levels. *Build. Environ.* **2020**, *183*, 107117. [CrossRef]
11. Yang, J.; Wang, F.; Song, G.; Li, R.; Raj, U. Effects of clothing size and air ventilation rate on cooling performance of air ventlaiton clothing in a warm codnition. *Int. J. Occup. Saf. Ergon.* **2022**, *28*, 354–363. [CrossRef]
12. Kim, H.A. Moisture Vapor Permeability and Thermal Wear Comfort of Ecofriendly Fiber-Embedded Woven Fabrics for High-Performance Clothing. *Materials* **2021**, *14*, 6205. [CrossRef] [PubMed]
13. Gao, H.; Deaton, A.S.; Fang, X.; Watson, K.; DenHartog, E.A.; Barker, R. Effects of Environmental Temperature and Humidity on Evaporative Heat Loss through Firefighter Suit Materials Made with Semi-Permeable and Microporous Moisture Barriers. *Text. Res. J.* **2022**, *92*, 219–231. [CrossRef]
14. Wang, F.; Pang, D.; Liu, X.; Liu, M.; Du, W.; Zhang, Y.; Cheng, X. Progress in Application of Phase-Change Materials to Cooling Clothing. *J. Energy Storage* **2023**, *60*, 106606. [CrossRef]
15. Ke, Y.; Wang, F.; Xu, P.; Yang, B. On the Use of a Novel Nanoporous Polyethylene (nanoPE) Passive Cooling Material for Personal Thermal Comfort Management under Uniform Indoor Environments. *Build. Environ.* **2018**, *145*, 85–95. [CrossRef]
16. Liu, B.; Wang, H.; Lin, H.; Su, Y.; Wei, G.; Xu, Z. Effect of Phase Change Cooling Vest on Related Thermal Regulation Factors in Moderately Hot Environments. *Build. Environ.* **2023**, *242*, 110566. [CrossRef]
17. Zhang, M.; Li, Z.; Wang, Q.; Xu, Y.; Hu, P.; Zhang, X. Performance investigation of a portable liquid cooling garment using thermoelectric cooling. *Appl. Therm. Eng.* **2022**, *214*, 118830. [CrossRef]

18. Ma, Z.; Zhao, D.; Wang, F.; Yang, R. A Novel Thermal Comfort and Energy Saving Evaluation Model for Radiative Cooling and Heating Textiles. *Energy Build.* **2022**, *258*, 111842. [CrossRef]
19. Rykaczewski, K. Rational Design of Sun and Wind Shaded Evaporative Cooling Vests for Enhanced Personal Cooling in Hot and Dry Climates. *Appl. Therm. Eng.* **2020**, *171*, 115122. [CrossRef]
20. Choudhary, B.; Udayraj; Wang, F.; Ke, Y.; Yang, J. Development and experimental validation of a 3D numerical mdel based on CFD of the human torso wearing air ventilation clothing. *Int. J. Heat Mass Transf.* **2020**, *147*, 118973.
21. Wang, F.; Song, W. An investigation of thermophysiological responses of human while using four personal cooling strategies during heatwaves. *J. Therm. Biol.* **2017**, *70*, 37–44. [CrossRef]
22. Wan, X.; Wang, F.; Udayraj. Numerical Analysis of Cooling Effect of Hybrid Cooling Clothing Incorporated with Phase Change Material (PCM) Packs and Air Ventilation Fans. *Int. J. Heat Mass Transf.* **2018**, *126*, 636–648. [CrossRef]
23. Al Sayed, C.; Vinches, L.; Dupuy, O.; Douzi, W.; Dugue, B.; Hallé, S. Air/$CO_2$ Cooling Garment: Description and Benefits of Use for Subjects Exposed to a Hot and Humid Climate during Physical Activities. *Int. J. Min. Sci. Technol.* **2019**, *29*, 899–903. [CrossRef]
24. Zhao, M.; Gao, C.; Wang, F.; Kuklane, K.; Holmér, I.; Li, J. A Study on Local Cooling of Garments with Ventilation Fans and Openings Placed at Different Torso Sites. *Int. J. Ind. Ergon.* **2013**, *43*, 232–237. [CrossRef]
25. Wang, F.; Chow, C.S.W.; Zheng, Q.; Ke, Y.; Yang, B.; Zheng, X.; Noor, N.; Zhang, Q.; Zhang, C.; Zhou, H. On the Use of Personal Cooling Suits to Mitigate Heat Strain of Mascot Actors in a Hot and Humid Environment. *Energy Build.* **2019**, *205*, 109561. [CrossRef]
26. Peng, Y.; Li, W.; Liu, B.; Jin, W.; Schaadt, J.; Tang, J.; Zhou, G.; Wang, G.; Zhou, J.; Zhang, C.; et al. Integrated Cooling (i-Cool) Textile of Heat Conduction and Sweat Transportation for Personal Perspiration Management. *Nat. Commun.* **2021**, *12*, 6122. [CrossRef]
27. Ernst, T.C.; Garimella, S. Demonstration of a Wearable Cooling System for Elevated Ambient Temperature Duty Personnel. *Appl. Therm. Eng.* **2013**, *60*, 316–324. [CrossRef]
28. Yang, J.; Zhang, Y.; Huang, Y.; Chen, W. Effects of Liquid Cooling Garment on Physiological and Psychological Strain of Firefighter in Hot and Warm Environments. *J. Therm. Biol.* **2023**, *112*, 103487. [CrossRef]
29. Bartkowiak, G.; Dabrowska, A.; Marszalek, A. Assessment of an Active Liquid Cooling Garment Intended for Use in a Hot Environment. *Appl. Ergon.* **2016**, *58*, 182–189. [CrossRef]
30. Guo, T.; Shang, B.; Duan, B.; Luo, X. Design and Testing of a Liquid Cooled Garment for Hot Environments. *J. Therm. Biol.* **2015**, *49–50*, 47–54. [CrossRef]
31. Chen, W.Y.; Shi, X.L.; Zou, J.; Chen, Z.G. Thermoelectric Coolers for On-Chip Thermal Management: Materials, Design, and Optimization. *Mater. Sci. Eng. R Rep.* **2022**, *151*, 100700. [CrossRef]
32. Jeong, E.S. A New Approach to Optimize Thermoelectric Cooling Modules. *Cryogenics* **2014**, *59*, 38–43. [CrossRef]
33. Xu, Y.; Li, Z.; Wang, J.; Zhang, M.; Jia, M.; Wang, Q. Man-Portable Cooling Garment with Cold Liquid Circulation Based on Thermoelectric Refrigeration. *Appl. Therm. Eng.* **2022**, *200*, 117730. [CrossRef]
34. Shu, W.; Wang, J.; Zhang, X.; Luo, X. A Statistical Study to Evaluate the Performance of Liquid Cooling Garments Considering Thermal Comfort. In Proceedings of the ASME 2019 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems, Anaheim, CA, USA, 7–9 October 2019; Volume 12. [CrossRef]
35. Zhang, M.; Li, Z.; Wang, Q.; Yuan, T.; Xu, Y. Research on Refrigerant Optimization and Characteristic Parameters Based on Thermoelectric Refrigeration Cooling Garment. *Appl. Therm. Eng.* **2022**, *212*, 118606. [CrossRef]
36. Rehman, T.-; Ali, H.M. Experimental Study on the Thermal Behavior of RT-35HC Paraffin within Copper and Iron-Nickel Open Cell Foams: Energy Storage for Thermal Management of Electronics. *Int. J. Heat Mass Transf.* **2020**, *146*, 118852. [CrossRef]
37. Tauseef-ur-Rehman; Ali, H.M.; Janjua, M.M.; Sajjad, U.; Yan, W.M. A Critical Review on Heat Transfer Augmentation of Phase Change Materials Embedded with Porous Materials/Foams. *Int. J. Heat Mass Transf.* **2019**, *135*, 649–673. [CrossRef]
38. Nazir, H.; Batool, M.; Osorio, F.J.B.; Isaza-Ruiz, M.; Xu, X.; Vignarooban, K.; Phelan, P.; Inamuddin; Kannan, A.M. Recent Developments in Phase Change Materials for Energy Storage Applications: A Review. *Int. J. Heat Mass Transf.* **2019**, *129*, 491–523. [CrossRef]
39. Khan, Z.; Khan, Z.; Ghafoor, A. A Review of Performance Enhancement of PCM Based Latent Heat Storage System within the Context of Materials, Thermal Stability and Compatibility. *Energy Convers. Manag.* **2016**, *115*, 132–158. [CrossRef]
40. Butts, C.L.; Torretta, M.L.; Smith, C.R.; Petway, A.J.; McDermott, B.P. Effects of a Phase Change Cooling Garment during Exercise in the Heat. *Eur. J. Sport Sci.* **2017**, *17*, 1065–1073. [CrossRef] [PubMed]
41. Qiao, Y.; Cao, T.; Muehlbauer, J.; Hwang, Y.; Radermacher, R. Experimental Study of a Personal Cooling System Integrated with Phase Change Material. *Appl. Therm. Eng.* **2020**, *170*, 115026. [CrossRef]
42. Zhang, R.; Chen, D.; Chen, L.; Cao, X.; Li, X.; Qu, Y. Preparation and Thermal Properties Analysis of Fatty Acids/1-Hexadecanol Binary Eutectic Phase Change Materials Reinforced with $TiO_2$ Particles. *J Energy Storage* **2022**, *51*, 104546. [CrossRef]
43. Chen, Q.; Wang, H.; Gao, H.; Wang, X.; Ma, B. Effects of Porous Silicon Carbide Supports Prepared from Pyrolyzed Precursors on the Thermal Conductivity and Energy Storage Properties of Paraffin-Based Composite Phase Change Materials. *J. Energy Storage* **2022**, *56*, 106046. [CrossRef]
44. Chen, K.; Guo, L.; Wang, H. A Review on Thermal Application of Metal Foam. *Sci. China Technol. Sci.* **2020**, *63*, 2469–2490. [CrossRef]

45. Ma, F.; Liu, L.; Ma, L.; Zhang, Q.; Li, J.; Jing, M.; Tan, W. Enhanced Thermal Energy Storage Performance of Hydrous Salt Phase Change Material via Defective Graphene. *J. Energy Storage* **2022**, *48*, 104064. [CrossRef]
46. Ayaz, H.; Chinnasamy, V.; Jeon, Y.; Cho, H. Thermo-Physical Studies and Corrosion Analysis of Caprylic Acid–Cetyl Alcohol Binary Mixture as Novel Phase Change Material for Refrigeration Systems. *Energy Rep.* **2022**, *8*, 7143–7153. [CrossRef]
47. Tesař, V.; Kordík, J. Energy Storage in Macro-Capsules for Thermal Comfort Garments. *J. Energy Storage* **2019**, *25*, 100842. [CrossRef]
48. Tesař, V.; Kordík, J. Melting N-Eicosane in Scaled-up Model of Capsule for Use in Hot Climate Thermal-Comfort Garments. *EPJ Web Conf.* **2019**, *213*, 02086. [CrossRef]
49. Butts, C.L.; Smith, C.R.; Ganio, M.S.; McDermott, B.P. Physiological and Perceptual Effects of a Cooling Garment during Simulated Industrial Work in the Heat. *Appl. Ergon.* **2017**, *59*, 442–448. [CrossRef]
50. Sanchez-Marin, F.J.; Calixto-Carrera, S.; Villaseñor-Mora, C. Novel Approach to Assess the Emissivity of the Human Skin. *JBO* **2009**, *14*, 024006. [CrossRef]
51. Tong, J.K.; Huang, X.; Boriskina, S.V.; Loomis, J.; Xu, Y.; Chen, G. Infrared-Transparent Visible-Opaque Fabrics for Wearable Personal Thermal Management. *ACS Photonics* **2015**, *2*, 769–778. [CrossRef]
52. Hardy, J.D.; DuBois, E.F. Regulation of Heat Loss from the Human Body. *Proc. Natl. Acad. Sci. USA* **1937**, *23*, 624–631. [CrossRef]
53. Cai, L.; Song, A.Y.; Li, W.; Hsu, P.-C.; Lin, D.; Catrysse, P.B.; Liu, Y.; Peng, Y.; Chen, J.; Wang, H.; et al. Spectrally Selective Nanocomposite Textile for Outdoor Personal Cooling. *Adv. Mater.* **2018**, *30*, 1802152. [CrossRef] [PubMed]
54. Gu, B.; Xu, Q.; Wang, H.; Pan, H.; Zhao, D. A Hierarchically Nanofibrous Self-Cleaning Textile for Efficient Personal Thermal Management in Severe Hot and Cold Environments. *ACS Nano* **2023**, *17*, 18308–18317. [CrossRef] [PubMed]
55. Iqbal, M.I.; Lin, K.; Sun, F.; Chen, S.; Pan, A.; Lee, H.H.; Kan, C.-W.; Lin, C.S.K.; Tso, C.Y. Radiative Cooling Nanofabric for Personal Thermal Management. *ACS Appl. Mater. Interfaces* **2022**, *14*, 23577–23587. [CrossRef] [PubMed]
56. Zhu, F.; Feng, Q. Recent Advances in Textile Materials for Personal Radiative Thermal Management in Indoor and Outdoor Environments. *Int. J. Therm. Sci.* **2021**, *165*, 106899. [CrossRef]
57. Li, Z.; Chen, Q.; Song, Y.; Zhu, B.; Zhu, J. Fundamentals, Materials, and Applications for Daytime Radiative Cooling. *Adv. Mater. Technol.* **2020**, *5*, 1901007. [CrossRef]
58. Lin, K.T.; Han, J.; Li, K.; Guo, C.; Lin, H.; Jia, B. Radiative Cooling: Fundamental Physics, Atmospheric Influences, Materials and Structural Engineering, Applications and Beyond. *Nano Energy* **2021**, *80*, 105517. [CrossRef]
59. Hsu, P.C.; Song, A.Y.; Catrysse, P.B.; Liu, C.; Peng, Y.; Xie, J.; Fan, S.; Cui, Y. Radiative Human Body Cooling by Nanoporous Polyethylene Textile. *Science* **2016**, *353*, 1019–1023. [CrossRef]
60. Peng, Y.; Chen, J.; Song, A.Y.; Catrysse, P.B.; Hsu, P.-C.; Cai, L.; Liu, B.; Zhu, Y.; Zhou, G.; Wu, D.S.; et al. Nanoporous Polyethylene Microfibres for Large-Scale Radiative Cooling Fabric. *Nat. Sustain.* **2018**, *1*, 105–112. [CrossRef]
61. Hsu, P.C.; Liu, C.; Song, A.Y.; Zhang, Z.; Peng, Y.; Xie, J.; Liu, K.; Wu, C.L.; Catrysse, P.B.; Cai, L.; et al. A Dual-Mode Textile for Human Body Radiative Heating and Cooling. *Sci. Adv.* **2017**, *3*, e1700895. [CrossRef]
62. Raman, A.P.; Anoma, M.A.; Zhu, L.; Rephaeli, E.; Fan, S. Passive Radiative Cooling below Ambient Air Temperature under Direct Sunlight. *Nature* **2014**, *515*, 540–544. [CrossRef]
63. Li, W.; Shi, Y.; Chen, Z.; Fan, S. Photonic Thermal Management of Coloured Objects. *Nat. Commun.* **2018**, *9*, 4240. [CrossRef] [PubMed]
64. Yu, Z.; Gao, Y.; Di, X.; Luo, H. Cotton Modified with Silver-Nanowires/Polydopamine for a Wearable Thermal Management Device. *RSC Adv.* **2016**, *6*, 67771–67777. [CrossRef]
65. Wei, W.; Wu, B.; Guo, Y.; Hu, Y.; Liao, Y.; Wu, C.; Zhang, Q.; Li, Y.; Chen, J.; Hou, C.; et al. A Multimodal Cooling Garment for Personal Thermal Comfort Management. *Appl. Energy* **2023**, *352*, 121973. [CrossRef]
66. Xu, P.; Kang, Z.; Wang, F.; Udayraj. A Numerical Analysis of the Cooling Performance of a Hybrid Personal Cooling System (HPCS): Effects of Ambient Temperature and Relative Humidity. *Int. J. Environ. Res. Public Health* **2020**, *17*, 4995. [CrossRef]
67. Ni, X.; Yao, T.; Zhang, Y.; Zhao, Y.; Hu, Q.; Chan, A.P.C. Experimental Study on the Efficacy of a Novel Personal Cooling Vest Incorporated with Phase Change Materials and Fans. *Materials* **2020**, *13*, 1801. [CrossRef]
68. Sajawal, M.; Rehman, T.; Ali, H.M.; Sajjad, U.; Raza, A.; Bhatti, M.S. Experimental Thermal Performance Analysis of Finned Tube-Phase Change Material Based Double Pass Solar Air Heater. *Case Stud. Therm. Eng.* **2019**, *15*, 100543. [CrossRef]
69. Dhumane, R.; Qiao, Y.; Ling, J.; Muehlbauer, J.; Aute, V.; Hwang, Y.; Radermacher, R. Improving System Performance of a Personal Conditioning System Integrated with Thermal Storage. *Appl. Therm. Eng.* **2019**, *147*, 40–51. [CrossRef]
70. Gharbi, S.; Harmand, S.; Jabrallah, S.B. Experimental Study of the Cooling Performance of Phase Change Material with Discrete Heat Sources—Continuous and Intermittent Regimes. *Appl. Therm. Eng.* **2017**, *111*, 103–111. [CrossRef]
71. Kang, Z.; Udayraj; Wan, X.; Wang, F. A New Hybrid Personal Cooling System (HPCS) Incorporating Insulation Pads for Thermal Comfort Management: Experimental Validation and Parametric Study. *Build. Environ.* **2018**, *145*, 276–289. [CrossRef]
72. Lou, L.; Zhou, Y.; Yan, Y.; Hong, Y.; Fan, J. Wearable Cooling and Dehumidifying System for Personal Protective Equipment (PPE). *Energy Build.* **2022**, *276*, 112510. [CrossRef]
73. Ge, F.; Wang, C. Exergy Analysis of Dehumidification Systems: A Comparison between the Condensing Dehumidification and the Desiccant Wheel Dehumidification. *Energy Convers. Manag.* **2020**, *224*, 113343. [CrossRef]
74. Lou, L.; Chen, K.; Fan, J. Advanced Materials for Personal Thermal and Moisture Management of Health Care Workers Wearing PPE. *Mater. Sci. Eng. R Rep.* **2021**, *146*, 100639. [CrossRef]

75. Wang, F.; Zhou, X.; Wang, S. Development processes and property measurements of moisture absorption and quick dry fabrics. *Fibres Text. East. Eur.* **2009**, *17*, 46–49.
76. Zeng, S.; Pian, S.; Su, M.; Wang, Z.; Wu, M.; Liu, X.; Chen, M.; Xiang, Y.; Wu, J.; Zhang, M.; et al. Hierarchical-Morphology Metafabric for Scalable Passive Daytime Radiative Cooling. *Science* **2021**, *373*, 692–696. [CrossRef] [PubMed]
77. Rother, M.; Barmettler, J.; Reichmuth, A.; Araujo, J.V.; Rytka, C.; Glaied, O.; Pieles, U.; Bruns, N. Self-Sealing and Puncture Resistant Breathable Membranes for Water-Evaporation Applications. *Adv. Mater.* **2015**, *27*, 6620–6624. [CrossRef]
78. Nayak, R.; Kanesalingam, S.; Houshyar, S.; Wang, L.; Padhye, R.; Vijayan, A. Evaluation of Thermal, Moisture Management and Sensorial Comfort Properties of Superabsorbent Polyacrylate Fabrics for the Next-to-Skin Layer in Firefighters' Protective Clothing. *Text. Res. J.* **2018**, *88*, 1077–1088. [CrossRef]
79. Bhuiyan, M.A.R.; Wang, L.; Shanks, R.A.; Ding, J. Polyurethane–Superabsorbent Polymer-Coated Cotton Fabric for Thermophysiological Wear Comfort. *J. Mater. Sci.* **2019**, *54*, 9267–9281. [CrossRef]
80. Yang, Y.; Rana, D.; Lan, C.Q.; Matsuura, T. Development of Membrane-Based Desiccant Fiber for Vacuum Desiccant Cooling. *ACS Appl. Mater. Interfaces* **2016**, *8*, 15778–15787. [CrossRef]
81. Li, Z.; Zhu, M.; Shen, J.; Qiu, Q.; Yu, J.; Ding, B. All-Fiber Structured Electronic Skin with High Elasticity and Breathability. *Adv. Funct. Mater.* **2020**, *30*, 1908411. [CrossRef]
82. Guan, M.; Li, J. Garment Size Effect of Thermal Protective Clothing on Global and Local Evaporative Cooling of Walking Manikin in a Hot Environment. *Int. J. Biometeorol.* **2020**, *64*, 485–499. [CrossRef]
83. Wang, F.; Annaheim, S.; Morrissey, M.; Rossi, R.M. Real evaporative cooling efficiency of one-layer tight-fitting sportswear in a hot environment. *Scand. J. Med. Sci. Sports* **2013**, *24*, e129–e139. [CrossRef] [PubMed]
84. Chen, Q.; Fan, J.T.; Sarkar, M.K. Biomimetics of Branching Structure in Warp Knitted Fabrics to Improve Water Transport Properties for Comfort. *Text. Res. J.* **2012**, *82*, 1131–1142. [CrossRef]
85. Miao, D.; Cheng, N.; Wang, X.; Yu, J.; Ding, B. Sandwich-Structured Textiles with Hierarchically Nanofibrous Network and Janus Wettability for Outdoor Personal Thermal and Moisture Management. *Chem. Eng. J.* **2022**, *450*, 138012. [CrossRef]
86. Guan, M.; Annaheim, S.; Li, J.; Camenzind, M.; Psikuta, A.; Rossi, R.M. Apparent Evaporative Cooling Efficiency in Clothing with Continuous Perspiration: A Sweating Manikin Study. *Int. J. Therm. Sci.* **2019**, *137*, 446–455. [CrossRef]
87. Wang, H.; Hu, S. Experimental Study on Thermal Sensation of People in Moderate Activities. *Build. Environ.* **2016**, *100*, 127–134. [CrossRef]
88. Zhao, M.; Gao, C.; Wang, F.; Kuklane, K.; Holmér, I.; Li, J. The Torso Cooling of Vests Incorporated with Phase Change Materials: A Sweat Evaporation Perspective. *Text. Res. J.* **2013**, *83*, 418–425. [CrossRef]
89. Itani, M.; Ghaddar, N.; Ghali, K. Innovative PCM-Desiccant Packet to Provide Dry Microclimate and Improve Performance of Cooling Vest in Hot Environment. *Energy Convers. Manag.* **2017**, *140*, 218–227. [CrossRef]
90. Luo, M.; Wang, Z.; Zhang, H.; Arens, E.; Filingeri, D.; Jin, L.; Ghahramani, A.; Chen, W.; He, Y.; Si, B. High-Density Thermal Sensitivity Maps of the Human Body. *Build. Environ.* **2020**, *167*, 106435. [CrossRef]
91. Liu, W.; Lian, Z.; Deng, Q.; Liu, Y. Evaluation of Calculation Methods of Mean Skin Temperature for Use in Thermal Comfort Study. *Build. Environ.* **2011**, *46*, 478–488. [CrossRef]
92. Chen, Y.; Su, Y.; Liu, G.; Zhao, P.; Tian, M.; Li, J. Design and Performance Evaluation of a Firefighting Protective Suit with an Incorporated Liquid-Cooled System. *Int. J. Occup. Saf. Ergon.* **2023**, *26*, 1–10. [CrossRef]
93. Hou, J.; Yang, Z.; Xu, P.; Huang, G. Design and Performance Evaluation of Novel Personal Cooling Garment. *Appl. Therm. Eng.* **2019**, *154*, 131–139. [CrossRef]
94. Golbabaei, F.; Heydari, A.; Moradi, G.; Dehghan, H.; Moradi, A.; Habibi, P. The Effect of Cooling Vests on Physiological and Perceptual Responses: A Systematic Review. *Int. J. Occup. Saf. Ergon.* **2020**, *28*, 223–255. [CrossRef] [PubMed]
95. Lapka, P.; Furmanski, P.; Wisniewski, T. Assessment of thermal performance of protective garments: The advanced numerical model. *Int. J. Numer. Methods Heat Fluid Flow* **2017**, *27*, 1078–1097. [CrossRef]
96. Rathour, R.; Das, A.; Alagirusamy, R. Study on the Influence of Constructional Parameters on Performance of Outer Layer of Thermal Protective Clothing. *J. Text. Inst.* **2023**, *114*, 1336–1346. [CrossRef]
97. Pearson, S.J.; Highlands, B.; Jones, R.; Matthews, M.J. Comparisons of Core Temperature between a Telemetric Pill and Heart Rate Estimated Core Temperature in Firefighters. *Saf. Health Work* **2022**, *13*, 99–103. [CrossRef] [PubMed]
98. Moran, D.S. Stress Evaluation by the Physiological Strain Index (PSI). *J. Physiol. Pharmacol.* **2000**, *11*, 403–423. [CrossRef]
99. Udayraj; Talukdar, P.; Das, A.; Alagirusamy, R. Heat and Mass Transfer through Thermal Protective Clothing—A Review. *Int. J. Therm. Sci.* **2016**, *106*, 32–56. [CrossRef]
100. Udayraj; Wang, F. A Three-Dimensional Conjugate Heat Transfer Model for Thermal Protective Clothing. *Int. J. Therm. Sci.* **2018**, *130*, 28–46. [CrossRef]
101. Liu, G.; Liang, S.; Hu, S. Calculation Method of Mean Skin Temperature Weighted by Temperature Sensitivity of Various Parts of Human Body. *J. Therm. Biol.* **2021**, *100*, 102995. [CrossRef]
102. Fan, J.; Chen, Y.S. Measurement of Clothing Thermal Insulation and Moisture Vapour Resistance Using a Novel Perspiring Fabric Thermal Manikin. *Meas. Sci. Technol.* **2002**, *13*, 1115. [CrossRef]
103. Wang, F. Measurements of clothing evaporative resistance using a sweating thermal manikin: An overview. *Ind. Health* **2017**, *55*, 473–484. [CrossRef] [PubMed]

104. Wang, F.; Havenith, G.; Mayor, T.S.; Kuklane, K.; Leonard, J.; Młynarcyk, M.; Hodder, S.; Wong, C.; Kishino, J.; Dai, X. Clothing real evaporative resistance determined by means of a sweating thermal manikin: A new round-robin study. In Proceedings of the 10th Internatinal Meeting on Thermal Manikin and Modelling (10i3m), Tampere, Finland, 7–9 September 2014.
105. Wang, F.; Kuklane, K.; Gao, C.; Holmér, I. Development and validity of a universal empirical equation to predict skin surface temperature on thermal manikins. *J. Therm. Biol.* **2010**, *35*, 197–203. [CrossRef]
106. Wang, F.; Lai, D.; Shi, W.; Fu, M. Effects of fabric thickness and material on apparent 'wet' conductive thermal resistance of knitted fabric 'skin' on sweating manikins. *J. Therm. Biol.* **2017**, *70*, 69–76. [CrossRef] [PubMed]
107. Takada, S.; Kobayashi, H.; Matsushita, T. Thermal Model of Human Body Fitted with Individual Characteristics of Body Temperature Regulation. *Build. Environ.* **2009**, *44*, 463–470. [CrossRef]
108. Li, F. A 3D Finite Element Thermal Model for Clothed Human Body. *JFBI* **2013**, *6*, 149–160. [CrossRef]
109. Enescu, D. Models and Indicators to Assess Thermal Sensation Under Steady-State and Transient Conditions. *Energies* **2019**, *12*, 841. [CrossRef]
110. Takada, S.; Sakiyama, T.; Matsushita, T. Validity of the Two-Node Model for Predicting Steady-State Skin Temperature. *Build. Environ.* **2011**, *46*, 597–604. [CrossRef]
111. Doherty, T.; Arens, E.A. *Evaluation of the Physiological Bases of Thermal Comfort Models*; American Society of Heating, Refrigerating and Air-Conditioning Engineers: Peachtree Corners, GA, USA, 1988.
112. Ooka, R.; Minami, Y.; Sakoi, T.; Tsuzuki, K.; Rijal, H.B. Improvement of Sweating Model in 2-Node Model and Its Application to Thermal Safety for Hot Environments. *Build. Environ.* **2010**, *45*, 1565–1573. [CrossRef]
113. Melnikov, V.; Krzhizhanovskaya, V.V.; Lees, M.H.; Sloot, P.M.A. System Dynamics of Human Body Thermal Regulation in Outdoor Environments. *Build. Environ.* **2018**, *143*, 760–769. [CrossRef]
114. Joshi, A.; Wang, F.; Kang, Z.; Yang, B.; Zhao, D. A three-dimensional thermoregulatory model for predicting human thermophysiological responses in various thermal environments. *Build. Environ.* **2022**, *207*, 108506. [CrossRef]
115. Katić, K.; Li, R.; Zeiler, W. Thermophysiological Models and Their Applications: A Review. *Build. Environ.* **2016**, *106*, 286–300. [CrossRef]
116. Stolwijk, J.A. Mathematical models of thermal regulation. *Ann. N. Y. Acad. Sci.* **1980**, *335*, 98–106. [CrossRef]
117. Munir, A.; Takada, S.; Matsushita, T. Re-Evaluation of Stolwijk's 25-Node Human Thermal Model under Thermal-Transient Conditions: Prediction of Skin Temperature in Low-Activity Conditions. *Build. Environ.* **2009**, *44*, 1777–1787. [CrossRef]
118. Kang, Z.; Wang, F.; Udayraj. An advanced three-dimensional thermoregulatory model of the human body: Development and validation. *Int. Commun. Heat Mass Transf.* **2019**, *107*, 34–43. [CrossRef]
119. Ismail, N.; Ghaddar, N.; Ghali, K. Predicting Segmental and Overall Ventilation of Ensembles Using an Integrated Bioheat and Clothed Cylinder Ventilation Models. *Text. Res. J.* **2014**, *84*, 2198–2213. [CrossRef]