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Review

Quantitative Comparison of Personal Cooling Garments in Performance and Design: A Review

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Abstract: Personal cooling garments (PCGs) have gained increasing attention as a promising solution to alleviate heat stress and enhance thermal comfort in hot and humid conditions. However, limited attention has been paid to the influence of clothing design on cooling performance. This review highlights the influence of design factors and provides a quantitative comparison in cooling performance for different types of PCGs, including air cooling garments, evaporative cooling garments, phase-change cooling garments, and liquid cooling garments. A detailed discussion about the relationship between design factors and the cooling performance of each cooling technique is provided based on the available literature. Furthermore, potential improvements and challenges in PCG design are explored. This review aims to offer a comprehensive insight into the attributes of various PCGs and promote interdisciplinary collaboration for improving PCGs in both cooling efficiency and garment comfort, which is valuable for further research and innovation.

Keywords: personal cooling garments; cooling technique; cooling performance; clothing design; quantitative comparison

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1. Introduction

Heat stress has become a growing concern with the impact of climate change. The high air temperatures, high relative humidity, high radiant temperature, and high activity levels or a combination of these factors present a significant challenge to both public health and occupational productivity [1–4]. Since humans can only regulate their core body temperature within a narrow range, excessive body heat beyond the capacity of physiological thermoregulation can result in heat accumulation. It may lead to a higher risk of heat-related illness and conditions such as dehydration, heat stroke, chronic kidney injuries, or even mortality [5–9].

Thermal comfort, as defined by the International Organization for Standardization [10], refers to the subjective state of an individual's satisfaction with the thermal environment. Individual differences in thermal comfort may exist in different climates as well as different physiological, behavioral, and cultural elements. Consequently, even when exposed to the same environmental conditions, individuals may perceive thermal comfort differently [11,12]. Finding acceptable temperatures for individuals depends on their opportunities to adjust conditions, such as changing their clothing or workplace to feel more comfortable. Although heating, ventilation, and air conditioning (HVAC) systems are commonly employed in indoor environments to lower temperatures and alleviate heat stress, they are primarily designed to cater to groups of occupants within buildings. Additionally, they are limited by energy requirements and operational costs, making them unsuitable for outdoor settings [13,14]. In contrast, personal cooling garments (PCGs) aim to provide direct thermal management to individuals, having been proven as an effective measure to manage the thermal state, satisfy individual thermal comfort needs, and improve working performance [15,16]. By focusing on individuals and offering personalized cooling solutions, PCGs offer a promising approach to address thermal comfort challenges in various situations.

Various types of PCGs have been investigated and reviewed in the past decade [17–24]. However, prior reviews primarily focused on the classification of PCG types, the introduction of materials, and potential applications; there is limited discussion about the quantitative comparison of different PCGs. Moreover, the factors of garment design that are closely related to the cooling performance are mentioned less in previous reviews. This paper aims to provide a comprehensive overview of the current state of the art, examine design factors associated with cooling efficiency, and conduct a quantitative comparison of different PCGs in critical aspects.

2. Methodology

2.1. Literature Search Strategy

Database searches were conducted in Google Scholar and Web of Science, covering the period from 1966 to 2023. All the terms that related to ‘personal cooling garment’ and ‘cooling power’ were searched through the Google Scholar system. The search strategy incorporated keywords and synonyms, which were searched in the title, abstract, or keyword fields of the databases. Moreover, to find more relevant studies, we surveyed journals using keywords that included ‘air cooling garment’, ‘evaporative cooling garments’, ‘phase change cooling garments’, ‘liquid cooling garments’, ‘thermoelectric cooling garments’, and ‘radiative cooling garments’. We also assessed all full-text papers for eligibility.

2.2. Selection Criteria

A systematic literature search was conducted to identify relevant articles, research papers, and studies related to personal cooling garments. The following criteria were used for source selection.

Inclusion criteria:

1. Peer-reviewed journal articles, conference papers, and academic studies.
2. Publications addressing personal cooling garments, technologies, and related topics.
3. Publications addressing cooling performance (e.g., cooling power).
4. Publications addressing the clothing design which affected the cooling performance.

Exclusion criteria:

1. Non-peer-reviewed sources, such as blog posts.
2. Publications that do not directly pertain to personal cooling.
3. Publications that do not assess the cooling performance (e.g., cooling power) of personal cooling garments.
4. Publications that do not related to garments.

3. Classification and Design Parameters

Personal cooling garments can be categorized into six different types based on the cooling technique used, namely, air cooling garments, evaporative cooling garments, phase-change cooling garments, liquid cooling garments, thermoelectric cooling garments, and radiative cooling garments. Detailed discussions such as the definition, principle, and design factors affecting the effectiveness of each category will be discussed in this section.

- Air cooling garments

Air cooling garments (ACGs) which improve the convective and evaporative heat dissipation of the human body can be classified into two types: active and passive ACGs. The active ACGs require batteries or external energy supplies to promote ventilative heat exchange within the clothing microenvironment. A forced convection can be introduced by electronic devices such as fans [25] (Figure 1a), vortex tubes [26] (Figure 1b), blowers [27], etc. In terms of garment design, to create sufficient air space between the garment and the human body, the outer layer of most active ACGs is usually made of wind-proof fabric to prevent air from escaping to the environment. In contrast, passive ACGs rely on air ventilation triggered by body movements and natural convection as well as the internal characteristics of textiles. The cooling effect can be regulated by the opening and mesh or spacer and mesh structures of a garment [28–31].

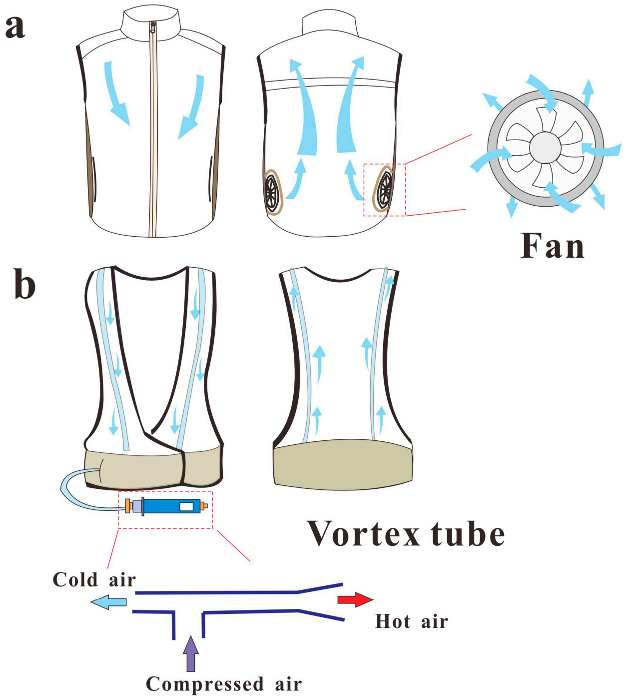

Figure 1. The schematic diagram of active air cooling garments (ACGs) (e.g., cooling achieved by fan (**a**) and vortex tube (**b**)).

The cooling effectiveness of ACGs can be affected by many factors, such as clothing design, environmental conditions, and the users. From the aspect of clothing design, these factors are related to the clothing size, the type of devices, the placement site of devices, the opening site, and the clothing eyelet. Zhao et al. [32] studied the design of locations for fans and openings at different torso sites. They found that the lower front placement site with both front and back openings achieved the best cooling performance. For the localized cooling, the ventilation location had more influence than the design of the opening. The ventilation units can be placed anywhere requiring more evaporative cooling. The adjustable openings (closed or opened) are helpful for the wearers' comfort but have no significant difference in the cooling performance under the same flow rate. Zhao et al. [33] investigated the effect of clothing eyelet designs (sizes and positions) for the air ventilation system and found that the eyelet could reduce the clothing bulkiness ($p < 0.05$) but had no significant impact on the cooling effectiveness ($p > 0.05$). Ho et al. [28] designed 10 different opening and mesh styles of T-shirts and found that the openings applied at two vertical side panels along the side seams of t-shirts were the most effective to release heat and moisture from the human body. Yang et al. [34] found that the upper body heat loss of ACGs was related to the combined influences of ventilation rate and clothing size. The ventilation rate can increase upper body heat loss, while the clothing size has almost no impact on the effectiveness in high ventilation. Yi et al. [25] evaluated different ventilation units for ACGs and found that ACGs with higher flow rates perform better, which can achieve a higher cooling power. Lou et al. [35] investigated the effects of garment design on cooling performance and recommended that the inner space between ACGs and the human body that may influence the efficiency of heat exchange is important for garment design.

In brief, ACGs provide an innovative approach to enhance thermal comfort and mitigate physiological strain. These cooling garments, which create an air gap between the body and clothing, coupled with active cooling mechanisms such as fans or blowers, offer effective heat dissipation. For the design of active ACGs, the eyelet design and adjustable openings are helpful for the bulkiness problem caused by the impermeable outer fabric; at the same time, the inner space between ACGs and the human body also needs to be considered in the design process. Placing devices with a higher flow rate at the sweating region is preferred for improving cooling efficiency, while the direct cooling of fans at their location may decrease the localized comfort sensation.

- Evaporative cooling garments

Evaporative cooling garments (ECGs) are based on the phase change of liquid (mostly water or sweat generated by the human body) from liquid to vapor state that can absorb heat for personal thermal management. As a passive cooling garment, it is energy-saving and environment-friendly. There are two mainly used ECGs (Figure 2): One is a liquid-soaked (water mainly) garment that provides cooling by direct contact with the skin surface; it should be dipped in liquid to reserve the cooling liquid in the garment before use. Another is dry evaporative cooling garments that need to be filled with water before use.

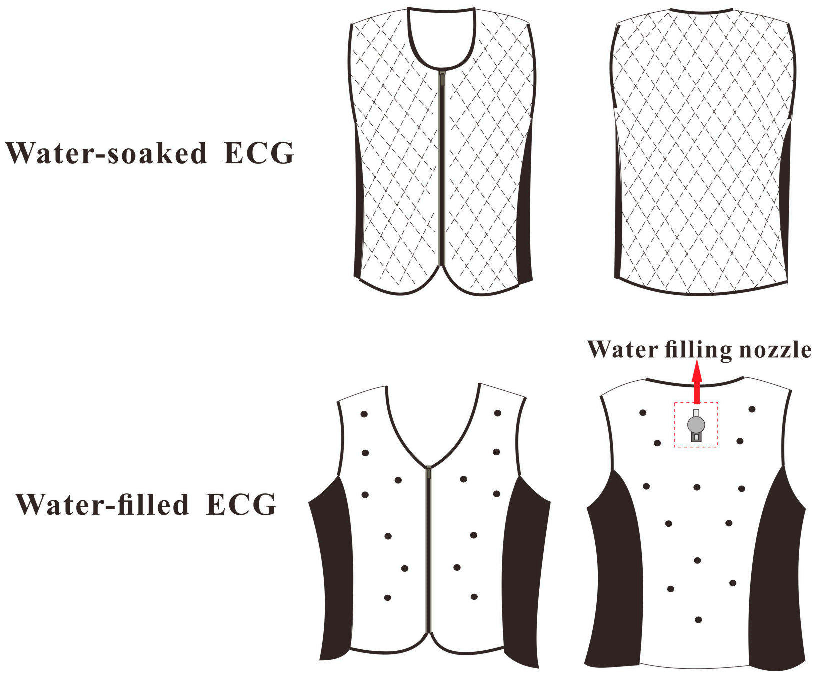

Figure 2. The schematic diagram of evaporative cooling garments (ECGs).

The cooling performance of the ECG is related to the properties of the clothing fabric, fitness, and ambient environment, such as the moisture evaporation and water vapor permeability of fabric and the air gap between the human body and clothing. For this type of garment, the cooling only happened on the outer clothing surface, not the inner surface. Hes et al. [36] studied the cooling effect of wet fabric with the fabric worn with or without an air gap between the skin and the fabric. They found that the cooling efficiency increased with the increase of the fabric moisture content without air layers, and if 2 mm and 4 mm thick air layers were involved, the total cooling efficiency would not be influenced by the water content. The better cooling performance happened when the fabric had direct contact with the skin. Guan et al. [37] studied the cooling power of ECGs that provide cooling by sweating from the human body and showed that the evaporative area and locus (in-plane and trans-plane moisture transfer) were determinants of the cooling efficiency. The cooling efficiency was negatively correlated with the evaporative resistance and the thickness of the fabric. Gillis et al. [38] assessed an ECG saturated with combined menthol and ethanol for evaporative cooling performance versus that with water and found that menthol and ethanol caused cooler sensations and a heat storage response.

ECGs utilize the natural phase change of water from liquid to vapor to provide effective personal cooling. They offer an energy-efficient and environmentally friendly approach to maintaining thermal comfort. To improve the cooling performance of ECGs, the first step is to increase the liquid content and ensure that the fabric has direct contact with skin. The second is to decrease the evaporative resistance and thickness of the fabric for ECGs.

- Phase-change cooling garments

Phase-change cooling garments (PCCGs) provide cooling through phase-change materials (PCMs) which can store latent heat for thermal energy transfer. PCMs can absorb heat from the body surface during the phase-change process that can increase the heat loss of the human body. PCMs can absorb or release heat at a constant temperature. Over 150 phase-change materials are used in scientific research [39]. Some commonly used PCMs are ice, frozen gel, and paraffin waxes. They have different phase-change temperatures (from 0–40 °C) and can be applied for various heat storage capacities [40]. There are two primary technologies used for the development of PCCGs. One is the phase-change material packs which can be placed inside the garment's pockets (Figure 3). The other is to incorporate PCMs into daily clothing, such as ordinary fabrics or fibers. (1) Phase-change microcapsules are PCMs packaged within a suitable wall material which can be impregnated or coated on the surface of the garment [41,42]. (2) Phase-change fiber is the PCM packaged inside a fiber that can be used in garment textiles [43,44]. However, the preparation process of phase-change microcapsules and fiber is complicated and costly, and most studies focus on the development of materials; there are limited studies about the cooling garments that are made by phase-change microcapsules and fiber.

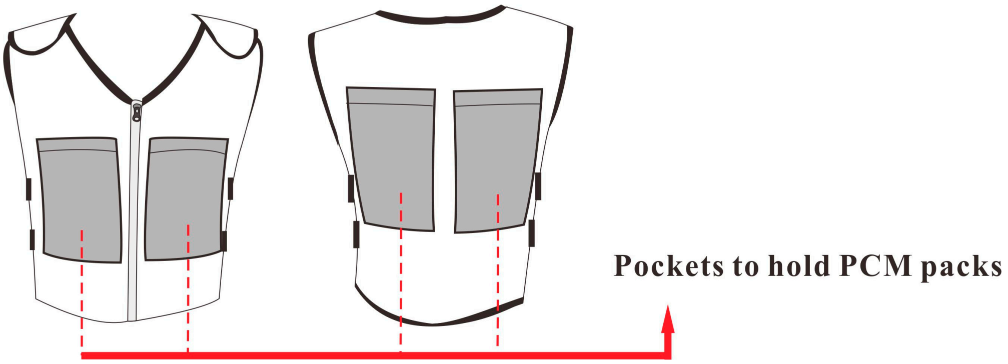

Figure 3. The schematic diagram of phase-change cooling garments (PCCGs).

The cooling effect of PCCGs mainly depends on the clothing design as well as the form and selection of PCMs. Yoo et al. [45] investigated the effects of the number and position of PCM-treated fabrics and found that the treated fabric with a greater amount of PCMs performed better. Moreover, if there is more than one layer, the outer layer of the garment is more appropriate for the effects of the PCMs. According to Mokhtari et al. [23], the PCM microcapsules can only provide a small capacity of heat absorption (about 15 W) with the limitation of the weight of materials that can be coated on the garment. Hence, they are not applicable in hot environments, where ice packs are more effective. House et al. [46] assessed the performance of four PCCGs containing different PCMs, which melted at 0 °C, 10 °C, 20 °C, and 30 °C separately, and the PCCGs were worn under firefighters' protective clothing. They found that 10 °C has the best cooling efficiency when combining work and rest periods, and they also stated that a cooling vest containing ice packs (melting at 0 °C) could be used only if the thermal resistance between the ice packs and the skin was higher. Gao et al. [47] evaluated PCCGs with different melting temperatures, masses, and covering areas and found that the PCCG with the lower melting temperature (24 °C) performed better than those with higher melting temperatures. They also found that the cooling performance was mainly determined by the covering area, while the cooling duration depended on the PCM mass. In hot climates, the temperature gradient for PCCGs was suggested to be equal to or greater than 6 °C.

PCCGs represent an innovative and promising solution for achieving effective cooling and enhancing thermal comfort in various environments. By harnessing the properties of PCMs that can change from solid to liquid and vice versa to create a cooling effect, these garments offer a unique approach to regulating body temperature. The design and composition of PCCGs play an important role in their cooling efficiency. A higher mass of PCMs or PCM microcapsules is positive for cooling efficiency, and the lower melting temperature can provide a higher cooling rate. The higher phase-transition temperature can provide a longer cooling duration. A temperature gradient over 6 °C is recommended. Ice packs can only be used when there is sufficient thermal resistance between the skin and ice. At the same time, the covering area needs to be considered in the design of PCCGs.

- Liquid cooling garments

Liquid cooling garments (LCGs) provide cooling by the pump-driven circulation of liquid coolant inside the tubes embedded in the garment (Figure 4). The tubes may be sewn into the fabric layer, and the pump is powered by electricity. The circulating liquid may be cold or icy water, liquid metal, or a mixture of water and propylene or ethylene glycol [48,49]. The liquid microclimate cooling systems produce a temperature gradient that makes the conductive and convective heat transfer take place among the coolant, the human body, and the environment.

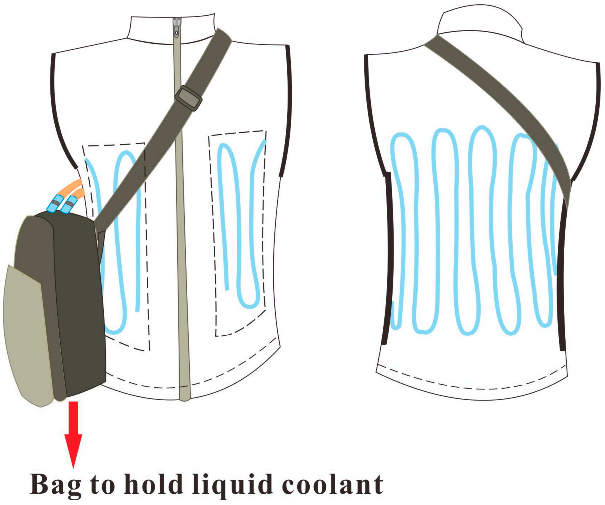

Figure 4. The schematic diagram of liquid cooling garments (LCGs).

The cooling performance of LCGs depends on the design of the clothing, the ambient condition, and the controller, which determines the liquid flow rate, coolant temperature, and intermittent or regional cooling control [50–54]. In terms of clothing design, it is related to the fitness, tubing characteristics, different body areas, and fabric [55–58]. Kayacan et al. [51] compared two different designed LCGs and found that the fabrics with a natural curved structure performed better than the plain fabrics; they also found that when the liquid inlet temperature was decreased, the effective cooling increased slightly. Burton et al. [52] found that the heat removal rate of LCGs was not linearly related to the flow rate when the flow was relatively slow. When the flow rate exceeds 1 L/min, little further improvement in the cooling performance can be made with the increase in flow rate. These findings were also shown by Frim et al. [50]. Dionne et al. [59] evaluated PCGs with different densities of tubing through thermal manikin testing. They found that under the condition of the same flow rate and liquid inlet temperature, the heat removal rate increased with the density of the tubing. Branson et al. [55] used a 3D body scanner to compare the fit analyses of LCGs and indicated that from the aspect of different users, it is better to develop an adjustable cooling garment. Cao et al. [58] investigated the effect of inner fabric layers of LCGs on heat exchange and cooling efficiency. They found that an inner layer with good thermal conductivity, good moisture management, and good tactile properties is desirable.

LCGs offer a promising approach to regulating body temperature and enhancing comfort. These garments utilize the circulation of cold liquid through tubes in clothing to facilitate heat exchange between the body, the liquid, and the environment. For the design of LCGs, a lower liquid temperature with a higher flow rate (no more than 1 L/min) is beneficial to improve cooling performance. As conductive heat transfer is the primary cooling mechanism for LCGs, a good fitness of LCGs can also increase cooling efficiency. An adjustable (fitness and flows) LCG could be designed to reduce the discomfort caused by the coolant having direct contact with skin, and a three-layer system may be better for wearer comfort. The comparative analysis of different LCGs demonstrates their varied cooling powers, durations, and temperature ranges, allowing for tailored choices based on specific cooling needs. Further exploration and real-world studies will contribute to a deeper understanding of LCGs' performance and their utility in diverse settings.

- Thermoelectric cooling garments

Thermoelectric cooling garments (TCGs) are based on the Peltier effect that can convert electrical energy into thermal power. The single-stage thermoelectric (TE) module is composed of type-N and type-P semiconductors which connected electrically in series. The Peltier effect can transfer heat from one side to the other; therefore, one face is heated and the opposite is cooled, which can be changed by the direction of the electric current [60,61]. A single TE device can be embedded in a clothing system to provide cooling by direct contact with the skin [62] (Figure 5). However, there are some apparent weaknesses in the design of such TCGs, for example, the poor coefficient of performance and low efficiency, so there is nearly no cooling garment designed solely using the Peltier effect. Some enhanced cooling garments, such as the combination of the air and TE cooling techniques which enhance air cooling through the TE unit [63,64] and the combination of the liquid and TE cooling techniques which enhance liquid cooling through the TE unit [64] were developed for better cooling performance.

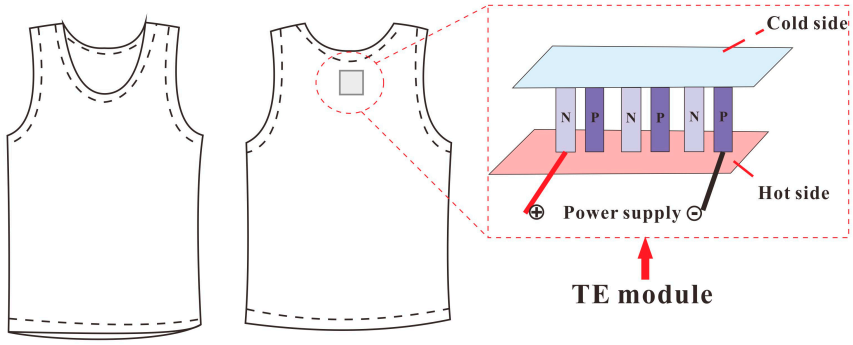

Figure 5. The schematic diagram of thermoelectric cooling garments (TCGs).

- Radiative cooling garments

Radiative cooling garments (RCGs) provide thermal comfort through enhanced radiative heat loss from the human skin or the clothing outer surface. Human skin can be regarded as a near-black radiating source with an emissivity value over 0.95 [65,66], which makes it a near-perfect emitter of thermal infrared radiation. Based on this concept, some fabrics, textiles, and garments were designed for personal thermal management. The cooling garment with mid-IR transparency [67], mid-IR emissivity [68], or solar-reflecting mid-IR emissivity [69] are all potential solutions to achieve better cooling efficiency. RCGs as passive cooling systems contribute to energy saving. The innovation of RCGs mainly focuses on the material design [70–73]; there is limited knowledge about the cooling performance of this kind of garment which may need more attention.

4. Comparative Study

Several methods have been employed to evaluate PCGs. Human trials, thermal manikin tests, and model simulation were the three mainly used methods for the assessment of PCGs [74]. Human testing provides practical data for the physiological impact of PCGs on the human body with the work intensity and specific test conditions set [75–77]. A sweating, heated manikin (ASTM F2371-16) can provide objective and reproducible results to assess the effectiveness of PCGs [78,79], while thermal manikins cannot simulate realistic thermo-physiological responses, such as changes in sweat and heart rate. Thermal manikins can be used as an alternative method when human trials are not applicable, while it cannot replace the human subject tests. Generally, human trials can be conducted independently or combined with thermal manikins to evaluate PCGs. Thermoregulation models could be a good alternative to human trial studies to avoid the ethical problems and operating limitations. Thermoregulation models that can simulate physiological responses and the complex heat transfer of the human body were developed to predict human thermal responses in different environmental and activity conditions [80–82]. However, thermoregulation models need to be combined with human trials to demonstrate their reliability and applicability. The evaluation of different types of PCGs plays an important role in the development and improvement of cooling technology. In this section, the separate and overall quantitative comparisons in cooling performance for different types of PCGs will be discussed.

Table 1 provides a comparative analysis of different ACGs based on key parameters such as cooling power, weight, duration, and flow rate. The cooling powers of the listed ACGs in Table 1 were measured through thermal manikin tests (ASTM-F2371-16). ACG 1, designed by Zhao et al. [32], demonstrates the highest estimated cooling power range of 71.5–106 W, while ACG 2 [83] offers a cooling power of 79.5–97.6 W, and the cooling temperature is 30 °C. ACG 3 [25] has a cooling power of approximately 67.72 W. ACG 4 [63] was proposed as a thermoelectric ACG, providing a personal cooling of 15.5 W. ACG 5 [84] was designed for healthcare workers and provides a constant cooling temperature of 22.85 °C and exhibits a cooling power of 51.7 W. Notably, these ACGs were tested under different environmental settings. ACG 4 [63] and ACG 5 [84] as the thermoelectric ACGs that can provide a lower cooling temperature through a thermoelectric unit are heavier than normal ACGs. The cooling duration of active ACGs mainly relies on the capacity of the cooling device's battery. Research by Yi et al. [25] highlights the positive impact of higher airflow rates on ACGs' performance. Additionally, the cooling coverage area is influenced by the positioning and outlet of the cooling mechanism.

Table 1. Quantitative analysis for air cooling garments (ACGs).

No.	Cooling Power	Weight	Duration	Testing Scenario	Flow Rate	Cooling Area
ACG 1	71.5–106 W	N/A	N/A	34 °C, 60% RH, 0.4 m/s	12 L/s	N/A
ACG 2	79.5–97.6 W	N/A	N/A	30–34 °C, 90% RH	10 m^3/h or 14 m^3/h.	0.53 m^2
ACG 3	67.72 ± 0.74 W	98 g (Fan only)	7.05 h	34 °C, 60% RH, 0.4 ± 0.1 m/s	8–22 L/s	N/A
ACG 4	15.5 W	994 g	N/A	26.1 °C, 50% RH	1×10^{-3}~1.17×10^{-3} m^3/s	N/A
ACG 5	51.7 W	1.2 kg	N/A	23 °C, 50% RH	70 L/min	N/A

Table 2 offers a comprehensive insight into the characteristics and performances of different PCCGs as assessed in various studies. The cooling power of PCCGs 1—3 were measured through thermal manikin tests (ASTM-F2371-16), the value of PCCG 4 was calculated from the average evaporation heat flux using an equation, and the value of PCCG

5 was simulated through Stolwijk's mathematical modeling [85]. A notable observation is the variability in cooling power across the examined cooling garments, ranging from 6.0 to 98.6 W. Regarding cooling duration, the assessed garments demonstrate a range from 65 to 360 min, suggesting varying capacities for sustained cooling during use. In addition, the garments were evaluated under different testing scenarios, encompassing diverse conditions such as hot climates and specific temperature gradients, which are significant factors influencing their efficacy. PCCG 1 [47] exhibits varying cooling powers, ranging from 6 to 28.4 W based on different phase-transition temperatures. The lower phase-transition temperature can provide a longer cooling duration, and the duration of the cooling is from 2.5 to 6 h. PCCG 2 [76] achieves cooling powers of 8.4 W and 10.5 W, with a weight of 1296 g. It operates for durations of 65 min and 125 min which depends on the different phase-transition temperatures. The cooling mechanism involves a dual-phase transition at 15 °C + 15 °C and 15 °C + 23 °C, contributing to the flexibility of the garment in addressing different thermal requirements. PCCG 3 [86] emphasizes its cooling power from 10–20 W and its weight of 2224 g. It sustains cooling for an extended duration of 210 min under specific testing conditions. PCCG 4, designed by Yang et al. [77], is based on the concept of vacuum desiccant cooling and emphasizes an average cooling power of 89.6 ± 9 W with a weight of 3400 g. It can achieve a minimum cooling temperature of 16 °C. Hou et al. [87] proposed a PCM-liquid cooling garment (PCCG 5) to enhance PCCGs; it demonstrates a cooling power ranging from 13.4 to 19.4 W, optimized for a prolonged usage of over 2 h under a testing scenario of 30 °C and 45% relative humidity.

Table 2. Quantitative analysis for phase-change cooling garments (PCCGs).

NO.	Cooling Power	Weight	Duration	Testing Scenario	Phase-Transition Temperature	Cooling Area	Cooling Temperature
PCCG 1	19.2–28.4 W	2224 g	150 min	Hot climates (the required temperature gradient is suggested to be greater than 6 °C)	24 °C	0.2054 m^2	≥24 °C
	12.9–21.2 W	2226 g	288 min		28 °C		≥28 °C
	6.0–14.2 W	1973 g	360 min		32 °C		≥32 °C
PCCG 2	8.4 W	1296 g	65 min	30 ± 0.5 °C, 80 ± 5% RH, <0.1 m/s	15°C + 15 °C	0.1404 m^2	≥15 °C
	10.5 W		125 min		15°C + 23 °C		≥15 °C
PCCG 3	10–20 W	2224 g	210 min	34 ± 0.5 °C, 60% RH, 0.4 m/s	21 °C	0.57 m^2	≥21 °C
PCCG 4	89.6 ± 9 W	3400 g	N/A	37 °C, 50% RH	N/A	0.4 m^2	≥16 °C
PCCG 5	13.4–19.4 W	1800 g	≥2 h	30 °C, 45% RH	24–26 °C	N/A	≥24 °C

Table 3 provides a comparison of four LCGs based on these parameters including cooling power, weight, duration, testing scenario, flow rate, cooling area, and cooling temperature. The cooling power of the LCG 1 and LCG 4 is calculated through equations, the value of LCG 2 is estimated by analysis, and the value of LCG 3 is estimated through the previous study [88]. LCG 1, designed by Guo et al. [89], demonstrates the estimated cooling power range of 67.2–138.1 W with a weight of 1.5 kg, and it offers a cooling duration of 0.79 to 3.36 h, tested within a temperature range of 40 °C to 50 °C. Meanwhile, LCG 2 [90] offers a relatively higher cooling power of 300 W, and its weight is less than 10 kg; it provided cooling for a minimum of 1 h under varying conditions of 30–45 °C in temperature and 20–80% relative humidity. LCG 3 [91] has a cooling power of 90.8–96.5 W with a weight of 3 kg, offering a cooling duration of 1.5 h within the specific conditions of 35.89 °C ± 1.25 °C in temperature and 35% relative humidity. Notably, LCG 2 [90] achieves a cooling temperature range of 22 to 27 °C, whereas LCG 3 [91] achieves a lower cooling temperature range of 10 to 15 °C. LCG 4 which was designed by Xu et al. [64] and based on thermoelectric refrigeration exhibits a high cooling power of 340.4 W, thereby providing effective cooling in a 30 °C environment.

Table 3. Quantitative analysis for liquid cooling garments (LCGs).

NO.	Cooling Power	Weight	Duration	Testing Scenario	Flow Rate	Cooling Area	Cooling Temperature
LCG 1	67.2–138.1 W	1.5 kg	0.79–3.36 h	40 °C–50 °C	224.5–544.2 mL/min	0.568 m^2	N/A
LCG 2	300 W	<10 kg	≥1 h	30–45 °C, 20–80% RH	3.8 L/min	N/A	22–27 °C
LCG 3	90.8–96.5 W	3 kg	90 min	35.89 ± 1.25 °C, 35% RH	N/A		10–15 °C
LCG 4	340.4 W	N/A	N/A	30 °C	N/A	N/A	15.7 °C

Table 4 offers a comparative analysis of four different types of PCGs based on these parameters including cooling power, weight, duration, testing scenario, cooling area, and cooling temperature. The results show that the cooling powers of the different PCGs range from 6 to 340.4 W. The enhanced LCG which is based on thermoelectric refrigeration demonstrates the highest cooling power, while the PCCG exhibits the lowest. The estimated cooling power for ACGs, PCCGs, LCGs, and ECGs ranges from 15.5 to 106 W, 6–98.6 W, 67.2–340.4 W, and 48–57 W, respectively. Weight is an important consideration for portable cooling systems, and lighter systems are usually preferred [92]. The weight of the personal cooling garments listed in this table varies from less than 100 g to over 3000 g, and ACGs present a relatively lower weight among these cooling garments. The testing scenarios, including temperature, humidity, and air velocity, listed in the table are important for the evaluation and application of different cooling systems. Most cooling garments are designed for use in hot climates which are higher than 30 °C, and the recommended temperature gradient for PCCGs is suggested to be greater than 6 °C.

Table 4. Comparative analysis for different types of personal cooling garments (PCGs).

Ref.	Cooling Technique	Cooling Power	Weight	Duration	Testing Scenario	Cooling Area	Cooling Temperature
[32]	ACG	71.5–106 W	N/A	N/A	34 °C, 60% RH, 0.4 m/s	N/A	N/A
[83]		79.5–97.6 W	N/A	N/A	30–34 °C, 90% RH	0.53 m^2	30 °C
[25]		67.72 ± 0.74 W	98g (Fan only)	7.05 h	34 °C, 60% RH, 0.4 ± 0.1 m/s	N/A	N/A
[63]		15.5 W	994 g	N/A	26.1 °C, 50% RH	N/A	19.8–26.5 °C
[84]		51.7 W	1.2 kg	N/A	23 °C, 50% RH	N/A	N/A
[47]	PCCG	19.2–28.4 W 12.9–21.2 W 6.0–14.2 W	2224 g 2226 g 1973 g	2.5 h 4.8 h 6 h	Hot climates (the required temperature gradient is suggested to be greater than 6 °C)	0.2054 m^2	≥24 °C ≥28 °C ≥32 °C
[76]		8.4 W 10.5 W	1296 g	65 min 125 min	30 ± 0.5 °C, 80 ± 5% RH, <0.1m/s	0.1404 m^2	≥15 °C ≥15 °C
[86]		10–20 W	2224 g	210 min	34 ± 0.5 °C, 60% RH, 0.4 m/s	0.57 m^2	≥21 °C
[77]		89.6 ± 9 W	3400 g	N/A	37 °C, 50% RH	0.4 m^2	N/A
[87]		13.4–19.4 W	1800 g	≥2 h	30 °C, 45% RH	N/A	N/A
[89]	LCG	67.2–138.1 W	1500 g	0.79–3.36 h	40 °C–50 °C	0.568 m^2	N/A
[90]		300 W	<10 kg	≥1 h	30–45 °C, 20–80% RH	N/A	22–27 °C
[91]		90.8–96.5 W	3000 g	90 min	35.89 ± 1.25 °C, 35% RH		10–15 °C
[64]		340.4 W	N/A	N/A	30 °C		≥15.7 °C
[93]	ECG	48–57 W	N/A	N/A	40 °C, 10% RH	0.6 m^2	N/A

The duration of cooling is an important consideration when choosing a cooling system for a particular application. The cooling duration needs to be considered when selecting a cooling system for a particular application. The duration of cooling provided by each cooling technique ranges from less than an hour to several hours. For active ACGs, the cooling duration is dependent on the battery provided for the cooling device. For PCCGs, it is related to the weight, covering area, and cooling temperature of the PCM. For LCGs, it is influenced by the flow rate, weight, and temperature of the cooling liquid.

Additionally, the cooling area is more important for designers to achieve better cooling performance. The cooling temperature for active ACGs is related to the environmental temperature and cannot be controlled by users; PCCGs and LCGs' cooling temperature is related to the phase-transition temperature of the PCMs and the temperature of the cooling liquid, respectively, and both cannot be controlled manually; and for ECGs, water evaporation is highly wind-speed dependent.

5. Conclusions

This paper presents a literature review on the design and comparison of personal cooling garments. Based on the cooling technique, PCGs are divided into six different types, including ACGs, PCCGs, LCGs, ECGs, TCGs, and RCGs. A brief introduction of each kind of cooling system has been presented, and the cooling efficiency, design-affecting parameters were also discussed.

The results of this review reveal that the cooling power exhibited by different types of cooling garments varies. It seems that these cooling garments are effective at reducing the physiological strain in a hot environment. LCGs demonstrate a relatively higher cooling power, ranging from 67.2–340.4 W.

As a relatively lightweight cooling garment, the cooling efficiency of ACGs is sensitive to environmental factors such as humidity levels and air temperature. In addition, ACGs rely on the exchange of the air from the inside to the outside of clothing; it cannot work when worn underneath personal protective equipment (PPE). The active ACGs require a power source to operate, and this can be problematic in situations where a continuous power source is not readily available. The passive ACGs show limited cooling efficiency, but they are lightweight and no extra devices needed, which is suitable for sportswear. For the design of active ACGs, the fabric of the outer layer should be considered for the air circulation inside the clothing, and the incorporating features such as the eyelet design and adjustable openings can prove beneficial in mitigating the bulkiness problem. Furthermore, optimizing the placement of devices with higher flow rates in the sweating region is recommended to enhance cooling efficiency.

The suitability of LCGs and PCCGs as normal clothing is limited by their excessive weight, which in turn affects the duration of cooling provided. The weight can add bulk, making them less comfortable and practical for everyday use, especially in athletic settings. The LCGs and PCCGs typically have a limited cooling duration, and their cooling sources need to be recharged or replaced to maintain their function. This limitation can be a concern for individuals requiring long-lasting cooling, such as athletes during extended competitions. In terms of LCGs, optimizing the cooling performance involves utilizing a lower liquid temperature coupled with a higher flow rate (not exceeding 1 L/min). Additionally, the design of adjustable (fitness and flows) LCGs can minimize the discomfort resulting from direct contact between the coolant and the skin. For PCCGs, enhanced cooling efficiency can be achieved by increasing the mass of the PCMs or phase-change microcapsules. Lower melting temperatures of the PCM provide higher cooling rates. Finally, achieving a proper fit of LCGs and PCCGs is essential to enhance cooling efficiency.

The performance of ECGs is influenced by ambient temperature and humidity. In extremely hot or humid conditions, they may struggle to provide adequate cooling, especially for individuals engaged in strenuous activities. To enhance the cooling performance of direct ECGs, firstly, increasing the liquid content and ensuring direct contact between the fabric and the skin can enhance cooling efficiency. Secondly, reducing the evaporative resistance and the thickness of the fabric used in ECGs can promote improved cooling effects.

However, the detailed exploration of other cooling garments, such as TCGs and RCGs, remains relatively limited in current research. Thus, further investigations in these categories are warranted to expand our understanding and guide future advancements in this field.

Further research is needed to balance the function, ergonomics, and aesthetic design for different applications. The efficiency of these PCGs not only depends on the effect of the cooling performance but also the effects of ambient temperature and experimental protocol. Therefore, different designs based on the consideration of end-use scenarios is necessary for the improvement of PCGs. Moreover, the development of these types of PCGs requires the impact of human factors, including metabolic rates and physical activities, on individuals' responses during the use of cooling garments under normal working conditions and should be studied in the future.

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