PROTECTIVE CLOTHING AND THERMAL STRESS: INTEGRATING COOLING SYSTEMS FOR ENHANCED PERFORMANCE

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ABSTRACT: *In recent years, the increase in legal regulations concerning personal protection has been accompanied by a significant growth trend in the protective clothing industry. The primary purpose of protective clothing is to provide a barrier against biological, chemical, physical, and mechanical hazards in the relevant field. However, to support the wearer's performance, these garments are also expected to maintain the body's thermal balance and manage thermal stress, depending on environmental conditions. Research in this area has shown that protective clothing used in various fields often exhibits insufficient heat and moisture transfer ability, indicating deficiencies that need to be addressed based on their intended use. Particularly in products where textile material properties are prominent and effective—such as firefighter suits, CBRN suits, and surgical gowns—there is significant potential for development and application, making them attractive for innovative studies. Within the scope of this study, the active and passive cooling systems engineered to enhance heat transfer and decrease thermal stress will be given in detail.*

Keywords: *protective clothing, thermal stress, heat transfer, cooling system.*

ZAŠTITNA ODEĆA I TERMIČKI STRES: INTEGRACIJA SISTEMA ZA HLAĐENJE ZA POBOLJŠANE PERFORMANSE

APSTRAKT: *Poslednjih godina, povećanje zakonskih propisa u vezi sa ličnom zaštitom prati značajan trend rasta u industriji zaštitne odeće. Primarna svrha zaštitne odeće je da pruži barijeru protiv bioloških, hemijskih, fizičkih i mehaničkih opasnosti u relevantnoj oblasti. Međutim, da bi se podržale performanse korisnika, od ove odeće se takođe očekuje da održava termičku ravnotežu tela i upravlja termičkim stresom, u zavisnosti od uslova okoline. Istraživanja u ovoj oblasti su pokazala da zaštitna odeća koja se koristi u različitim oblastima često pokazuje nedovoljnu sposobnost prenosa toplote i vlage, što ukazuje na nedostatke koje treba rešiti na osnovu njihove namenjene upotrebe. Posebno kod proizvoda gde su svojstva tekstilnog materijala istaknuta i efikasna - kao što su vatrogasna odela, HBRN odela i hirurške mantile - postoji značajan potencijal za razvoj i primenu, što ih čini atraktivnim za inovativne studije. U okviru ove studije, detaljno će biti dati aktivni i pasivni sistemi hlađenja projektovani za poboljšanje prenosa toplote i smanjenje termičkog stresa.*

Ključne reči: *zaštitna odeća, termički stres, prenos toplote, sistem hlađenja.*

1. INTRODUCTION

In high-temperature environments, perspiration constitutes the primary physiological mechanism through which the human body dissipates excess heat. However, the efficiency of this process is markedly limited under conditions of elevated relative humidity (RH). In such contexts, adequate ventilation and air cooling become critical for effective heat transfer and for maintaining acceptable indoor air quality [1].

According to the theory of body heat balance, thermal comfort is achieved when the amount of heat produced by the body is approximately equal to the amount of heat lost to the environment. In extremely hot environments or during high activity levels, the only way for the body to lose excess heat is through the evaporation of sweat from the body. The rate of evaporative cooling depends on the vapor pressure gradient between the skin surface and the environment, as well as the speed of air movement in the microclimate [2].

Thermal stress can significantly reduce productivity and increase the risk of heat-related injuries for workers. Since thermal stress poses a threat to workers' lives, health, and productivity, the researchers have especially focused on various personal cooling systems [3]. These systems have found a wide range of applications in everyday life for the deliberate reduction of skin and body temperature. Various garments have been developed to assist sweating in hot environments (e.g., astronauts and military personnel) or to enhance athletic performance [4]. Each of these methods is effective in reducing thermal stress, alleviating physiological strain, and increasing work duration. However, lack of mobility, limited cooling capacity, logistics, cost, and other factors limit their practical applications [3]. Based on these requirements, this study presents an overview on thermal stress, cooling effect, and protective clothing specifically designed for use in this field.

2. PROTECTIVE CLOTHING

Protective textiles are a part of technical textiles that are defined as comprising all those textile-based products which are used principally for their performance or functional properties rather than their aesthetic or decorative characteristics. Protective clothing refers to garments and other fabric-related items designed to protect the wearer from harsh environmental effects that may result in injuries or death [5].

The global industrial protective clothing market size was reported by Grand View Research as USD 18,350.7 million in 2022 and is projected to reach USD 31,178.0 million by 2030, growing at a CAGR of 6.9% from 2023 to 2030. Rising awareness regarding the importance of preventing work-related fatal accidents is likely to propel market growth [6].

Protective clothes can be classified such as thermal protection, flame protection, chemical protection, mechanical impact protection, radiation protection, biological protection, electrical protection and wearer visibility in terms of end-use functions. Besides, according to end use applications, they can be also classified as industrial protective textiles, agricultural protective textiles, military protective textiles, civilian protective textiles, medical protective textiles, sports protective textiles and space protective textiles [7]. The relationship is indicated in Figure 1.

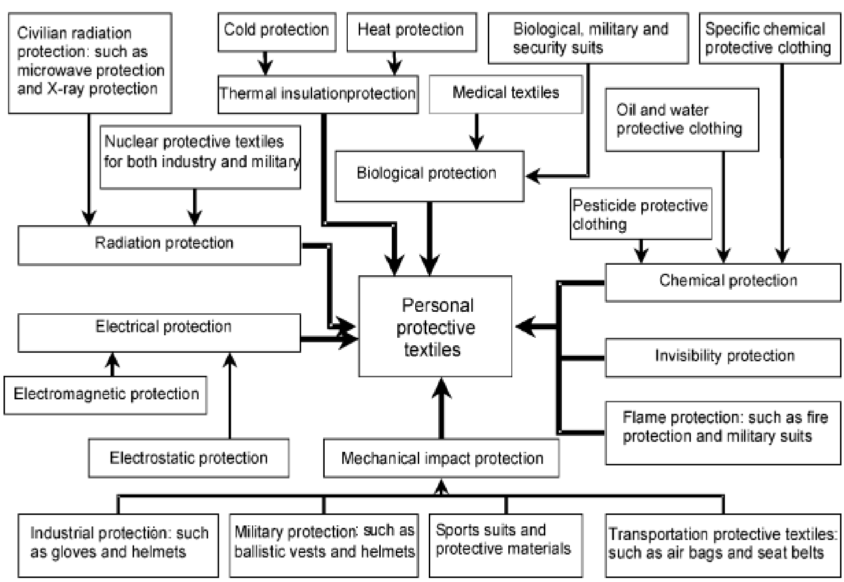

Figure 1: Classification of protective textiles [7]

In addition to specific barrier property, it is also expected to support the wearer's performance by maintaining the body's thermal balance and thereby managing thermal stress, particularly in relation to the environmental conditions in which they are used.

Clothing is the first protection against the heat wave coming from the outside. However, its thermal efficiency is time-limited due to its thermal properties, and it has the disadvantage of impairing metabolic heat and sweat evaporation. Therefore, harsh burns or heat stress can occur. There is a need for clothing solutions that eliminate overheating and automatically cool the body [8]. Therefore, it becomes essential to incorporate an additional layer into these specialized garments that provides a cooling effect, enhancing thermoregulatory performance by reducing thermal stress without compromising protective functionality.

3. THERMAL STRESS

Heat stress caused by prolonged exposure to high temperatures poses a significant threat to various biological systems. In other words, thermal stress refers to the strain on materials or biological tissues due to temperature changes. In humans, it is the physiological strain resulting from exposure to heat or cold; here, heat stress involves the body struggling to maintain a healthy core temperature. These issues require the development and implementation of effective heat stress reduction strategies [9]. Risks associated with heat exposure are more prevalent in some occupational environments, but implementation of heat management systems remains inadequate [10]. Adaptation and mitigation measures are essential to protect the workforce with the aim of improving both worker health and productivity [11]. Heat-related health and productivity consequences lead to social and economic costs for workers due to temporary or permanent health and quality of life impairments [12]. Future research should adopt an interdisciplinary approach that integrates social, economic, environmental, and technical dimensions to reduce these impacts [13].
Textile-based studies on heat stress reduction have been conducted. Nanoporous PE-containing fabrics have been shown to support directional moisture transport and maintain cooling performance while improving comfort [14]. Nanoporous polyethylene fabrics with ZnO nanoparticles were designed to reflect solar radiation while conducting body heat, reducing skin temperature by 5-13°C compared to cotton [15]. Flexible thermoelectric clothing has been found to maintain skin comfort at ambient temperatures up to 40°C under mild airflow [16]. Hybrid studies integrating thermoelectric micro/nanowires in fabrics have achieved cooling of approximately 5°C [17]. Shape memory polymers and dynamic structures allow textiles to actively adapt porosity or surface area in response to heat or humidity, improving ventilation and moisture management [18]. Textiles containing smart phase change materials can absorb heat during increasing temperature and release it when it is colder, supporting thermal comfort [19].

4. PERSONAL COOLING SYSTEMS

Personal cooling systems (PCS) currently play a crucial role in reducing thermal stress for athletes, firefighters, and workers exposed to extreme environmental conditions. These cooling garments can be categorized into two main types: passive and active systems. Passive garments do not rely on mechanical or electrical equipment; the main types include textile-based cooling and phase change materials (PCM). Well-known types of active garments are air-cooled garments (ACG), liquid-cooled garments (LCG), garments based on gas expansion and thermoelectric cooling devices, and hybrid cooling garments [Table 1; 20].

Air-cooled garments are relatively lightweight and help keep garments dry. They rely on the body's own mechanism (sweating) to dissipate heat, thus eliminating the risk of overcooling that may occur with other types of garments. However, in high relative humidity conditions, the efficiency of air-cooled garments decreases due to saturated ambient air. It has been concluded that pre-cooling the air before it passes over the skin can enhance performance in hot environments. The independence of air-cooled garments depends on battery-powered fans. Due to the low energy consumption of these fans, some garments can operate continuously for up to 12 hours. The air gap between the skin and the inner layer of the garment affects heat transfer. To maximize sweat evaporation, a gap between the skin and garment is recommended [2, 21, 30-37].

Liquid-cooled garments are heavier than those utilizing air-cooling. If the tubes embedded in the garment are compressed, fluid circulation may be disrupted. A cooling control mechanism is suggested to adjust cooling fluid temperature and circulation based on changes in skin temperature. However, if physical activity decreases, unwanted body heat loss may occur, leading to discomfort. In humid environments, if water circulates in the gap between the skin and the protective equipment, vapor formation may cause skin burns. If the ambient air temperature exceeds that of the coolant, the coolant may gain heat from the surroundings, reducing cooling efficiency [2, 3, 21, 38-42].

Garments based on gas expansion are lightweight but are believed to offer very limited operational duration compared to other cooling garments. Apart from the short operating time, the main issue is the release of CO_2 exhaust into the environment. If multiple users wear such garments in enclosed spaces, CO_2 concentration may reach hazardous levels [3, 43]. Garments based on thermoelectric cooling include thermoelectric devices (TEDs), which are solid-state refrigeration devices that can pump heat against a temperature difference and thus are suitable for personal cooling applications in hot environments. They have attracted significant interest in recent years due to their solid-state nature, readily adjustable cooling power and temperature, small form factor, and lightweight [16, 44-46].

Hybrid systems combine passive and active cooling techniques [21, 28, 47-55]. The most common hybrid garments are liquid-air cooling or phase change material-air cooling. Hybrid garments are generally more efficient than garments using a single technology. The effective cooling duration of a hybrid garment will be limited by the shortest duration among its combined technologies. For phase change material (PCM)-air cooled garments, PCM defines the effective cooling time [21]. The melting temperature of the PCM significantly affects the performance of the protective garment [55]. Once the PCM melts, the hybrid garment will continue to provide reduced cooling with the help of fans. However, these garments tend to be bulkier compared to conventional single-technology garme.

Table 1: Comparision of personal cooling sytems

		Mechanism	Advantages	Disadvantages	Applications	References
Passive Systems	Textile-based cooling	Reduce thermal resistance between skin and environment	Light, comfortable, effective in a wide range of environments, easy to maintain	Potential of skin irritation, expansive effectiveness, negligable cooling effect in very hot or humid environment	Sports, industrial, regular wear, military	4, 21-26
	Phase change materials-cooling	PCM absorbs heat during phase-change from solid to liquid	Simple, flexible, portable	Short cooling duration, limited capacity, possible flammability	Sports, industrial workers, outdoor use	2, 21, 27-29
Active Systems	Air-cooling	Air circulation to achieve perspiration evaporate	Long-term cooling, easy manufacturing, cheap, lightweight, high-performance, thermal comfort	Requires power, need to use porous fabric structure to enhance cooling effect	Sports, military, outdoor workers, firefighting	2, 21, 30-37
	Liquid-cooling	Cooling liquid circulation	Highly efficient, easy manufacturing, high cooling capacity	Large, heavy, risk of liquid leakage, requires power, potential safety risk, short operating time, risk of undesired body heat loss	Military, firefighting, industrial workers	2, 3, 21, 38-42
	Gas-cooling	Gas expansion cools via evaporation of liquified CO_2	No moving parts, cost-effective, portable, no external power required, lightweight	Limited cooling duration, potential toxicity	Outdoor activities	3, 43
	Thermoelectric cooler	Electric current creates hot and cold sides through the Peltier effect	Efficient cooling, small, lightweight, simple structure, lack of vibration, stable, noiseless and reliable, controllable	Expensive materials and manufacturing, high commercialization difficulty, limited cooling capacity, no larger and wearable active cooling garment, dissipating heat to the environment, brittle	Sports, military, outdoor recreation, consumer electronics	16, 44-46

Hybrid Systems	Combining active and passive systems	Improved performance, enhanced cooling efficiency, adaptability to various conditions, extended duration	Logistical complexity, increased weight and size, higher cost, require careful integration of components	Military, industrial, emergency response	21, 28, 47-55

3. CONCLUSION

The use of personal cooling garments can significantly improve human comfort and health in various hot environments. At the same time, they contribute to global efforts to reduce energy consumption and environmental pollution. However, an increasing number of factors must be considered due to the complexity of environmental conditions and human needs, while designing the cooling garments. These factors can be examined in three main groups: environment, clothing, and human body. Therefore, it is crucial to explore newly developed strategies that aim to improve the cooling properties of materials while also ensuring them lighter, more cost-effective, more environmentally friendly, and easier to manufacture. Additionally, personal cooling systems should be optimized and designed to include a wider range of parameters for assessing the performance of different personal cooling technologies.

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