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Thermal Management Technologies in Portable Cooling Vests: Development and Key Applications

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Abstract: With the acceleration of global warming and industrialization, high-temperature environments pose severe challenges to the health and work efficiency of outdoor workers, firefighters, military personnel, and aerospace operators. The traditional heat dissipation method of sweat evaporation is no longer sufficient to provide effective protection in extremely high-temperature and high-humidity environments. Portable cooling vests, as a type of personal protective equipment, are gaining increasing attention. This article describes in detail the development status and key technologies of portable cooling vests and discusses the impact of portable cooling vests on human thermal response, the applicability of liquid cooling technology, phase change materials (PCM), and microchannel heat exchangers, evaluates the application of the vest in terms of heat dissipation efficiency and user comfort, and a reference for the design of future portable cooling vests.

Keywords: cooling vest, thermal management, heat dissipation, phase change material application

1. Introduction

As the greenhouse effect increases and the global climate warms, people are experiencing increasingly hotter environments. In high-temperature environments, the traditional evaporative cooling effect of sweat is weakened, and heat stress caused by high-temperature work may have serious effects on workers' health [1].

If the metabolic heat generated by the human body cannot be dissipated to the surrounding environment in time, it will cause heat stress effects, affecting people's physiological functions and work efficiency. Therefore, a portable cooling vest is very important for outdoor heavy manual laborers. Wearing a cooling vest can effectively reduce the negative impact of high temperatures on the human body and improve people's comfort when working in high temperatures. At the same time, phase change materials and liquid cooling technology have been studied to alleviate heat stress reactions in such environments [1].In recent years, with advancements in technology, cooling vest designs have been continuously optimized [2].

By comprehensively analyzing the existing key technologies of portable cooling vests and their impact on human thermal response in high-temperature environments, this paper proposes to design and optimize suggestions to improve cooling efficiency, user comfort, and cost-effectiveness.

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This study provides a new theoretical basis for the design of portable cooling vests by analyzing and comparing the working mechanisms and application effects of different cooling technologies. It also promotes technological innovation in the field of convenient cooling. Research on the design and technology of cooling vests can improve cooling efficiency, significantly enhance workers' ability to work, and reduce the risk of high-temperature operations. This is of great significance to the life safety of outdoor heavy physical workers, military operations, aerospace, firefighting, and other fields.

2. Current development status of cooling vests

In order to achieve the goal of extravehicular activities in the US Gemini program, the problem of heat dissipation needs to be solved, and researchers have invented air-cooled jackets. Air-cooled clothing first obtains air from the environment through a fan installed on the surface of the clothing and then uses a refrigeration system to purify and cool the air. Finally, the cooled gas is blown onto the body and circulated around the human body, and heat is taken away by convection or evaporation to achieve a cooling effect. However, in space exploration, in a closed spacesuit, the air can only circulate internally. The continuous internal circulation causes the air humidity in the space suit to rise, causing fog to appear on the glass on the face of the spacesuit.

Water-cooling clothing was created by the Royal Aircraft Establishment in 1962 to protect people in the cockpit of an aircraft. Water-cooling clothing can significantly reduce the amount of sweat a person produces by circulating cold water through hoses, exchanging heat with the skin through the hoses.

In 2004, Japan already had "air-conditioning jackets" on the market. It installed a miniature electric fan in the jacket, sucking air into the jacket through the fan in the jacket, and then discharged from the exhaust port, taking away heat through the airflow, helping sweat evaporate, and cooling the body.

With the development of material science and micro-processing, the design trend of heat dissipation vests has gradually evolved towards lightweight, miniaturization and intelligence.

3. Heat dissipation technology

At present, portable cooling vests mainly use three types of technologies: liquid cooling technology, phase change material (PCM), and microchannel heat exchangers. The following is a detailed analysis and comparison of the working principles, feasibility, and comfort of these three technologies.

3.1. Liquid cooling technology and its characteristics

Liquid cooling leverages the high specific heat of liquids to absorb large amounts of heat with minimal temperature change, more efficient than that of simple fan-based systems [2-3].

By controlling the temperature and circulation speed of the coolant, liquid cooling technology can accurately adjust the cooling intensity to adapt to different ambient temperatures and human needs. This allows the liquid cooling system to be used not only in extremely high temperature environments, but also to adjust the cooling according to the actual environment. The liquid cooling system can provide a continuous and stable cooling effect, which is particularly suitable for cooling needs in long-term working environments [4].

Liquid cooling technology maintains a continuous flow of coolant through a circulating pump, so that its cooling effect is not limited by passive cooling methods such as phase change materials, and can provide long-term and stable cooling function.

3.2. Feasibility analysis

On the technical level, liquid cooling technology has been widely used in high-temperature and high-end environment fields such as aerospace, military industry, and firefighting, especially in work that requires long periods of time in a closed environment. For example, the liquid cooling suits used in the Apollo moon landing mission were an early typical application of liquid cooling technology, demonstrating its ability to effectively protect the wearer from high temperatures in extreme environments.

However, this technology also has its shortcomings. Early liquid cooling technology cooling vests required precise liquid circulation pipes to be embedded in the clothing, which increased the difficulty and cost of production. Because the liquid cooling system not only requires a reasonable pipeline layout to cover all areas that need cooling, but also needs to ensure the sealing and durability of the pipeline to avoid system failure due to liquid leakage. The design and manufacture of liquid cooling technology must take into account factors such as the circulation path, flow rate and temperature control of the liquid, which increases its complexity. Liquid cooling technology can provide extremely effective heat dissipation, but the overall weight of the system is relatively large. This technology is subject to certain limitations in portability and flexibility, especially in work that requires high-frequency activities. The weight of the vest and the complexity of the system may limit its widespread use in daily life.

However, as liquid cooling technology becomes smaller and cheaper, its feasibility is increasing. For example, the cooling vest developed in Germany distributes the cooling liquid evenly inside the vest through tiny pipes, achieving lightweight and efficient cooling.

3.3. Heat dissipation efficiency

The core advantage of liquid cooling is its ability to rapidly reduce body surface temperature and sustain cooling over long periods, because of the high specific heat of liquids.

While liquid cooling technology provides efficient heat dissipation, its comfort may be affected to a certain extent, mainly reflected in the weight, structural design and cooling effect control of the vest. Since the liquid cooling vest is embedded with coolant pipes, pumps and liquid storage systems, the overall weight is relatively high. At the same time, the liquid cooling system needs to be connected to an external power supply to circulate and cool the liquid, which also increases the weight and volume of the vest and limits its mobility. These irrational factors may make the wearer inconvenient and uncomfortable.

For the cooling process, liquid cooling systems have excellent cooling performance, but there is a potential risk of causing local overcooling of the human body, especially when the liquid temperature is low. Therefore, when manufacturing cooling vests, manufacturers usually add an additional isolation layer to prevent the liquid pipe from directly contacting the skin or choose to reduce the diameter of the pipe or reduce the flow rate and flow of the liquid in the pipe. This can reduce the direct stimulation of low-temperature liquid to the human body through these two aspects. Taking the German liquid cooling vest as an example, it can transmit 17°C coolant through tiny pipes, which can significantly reduce the temperature of the skin surface under high-temperature conditions while also avoiding excessive coldness [5].

4. Phase change materials

Phase Change Materials (PCM) are latent heat storage materials with high melting latent heat. Their high latent heat property enables them to store a large amount of heat at a nearly constant temperature. When the external temperature is higher than the phase change temperature, an endothermic phase change will occur. Otherwise, the opposite phase change process will occur. Because they can absorb

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a large amount of latent heat during the phase change process, they are widely used in personal protective equipment in high-temperature environments [3]. PCMs show good latent heat absorption performance in clothing and are widely used in temperature-regulating clothing, such as phase change microcapsules, phase change fibers, phase change packaging materials, etc. However, due to the limitations of phase change temperature, phase change form, and processing methods, only a few types of PCMs are suitable for cooling clothing.

4.1. Heat dissipation efficiency

The high latent heat properties of PCM enable it to store or release a large amount of energy per unit mass, which can provide a long cooling time.

The amount of PCM used is directly related to the cooling performance. Using more PCM will improve the thermal protection performance of the cooling clothing. However, increasing the amount of PCM will also increase the weight, overall hardness, and roughness of the clothing, affecting the wearing comfort. The appropriate PCM dosage and coverage area should be selected to optimize the heat dissipation performance [6].

Experiments have shown that the cooling effect of phase change microcapsules is weak because the coverage of the microcapsules is relatively small and it is difficult to meet the heat dissipation requirements. Theoretically, to effectively dissipate heat in a high-temperature environment, the human body needs at least 2 kg of phase change material. Therefore, in order to realize the application of a large amount of phase-change materials in clothing, people have developed a method of adding phase-change material packages to the interlayer of clothing. By designing pockets at multiple key heat-generating parts of clothing, phase change material packages are placed in these pockets to increase the heat absorption speed and extend the heat absorption time, thereby achieving a better cooling effect [2]. Adding an insulating layer can also reduce the interference of external temperature on the cooling system, thereby significantly extending the cooling time [7].

4.2. Feasibility

Phase change microcapsules are valued for their good temperature control effects, but their production process is complex and costly, with issues like poor air permeability limiting large-scale use. Electrospinning can produce phase change fibers but has low efficiency and involves high-voltage risks. Researchers are thus exploring more efficient, safer methods like centrifugal spinning. For example, Bao et al. prepared hydrophobic aerogel fibers with high latent heat and good mechanical properties, suitable for flexible, foldable fabrics at room temperature [6].

4.3. Comfort

When selecting materials to be placed close to the human body, materials close to the human body temperature should be chosen to avoid discomfort. Therefore, when selecting phase-change materials, low-temperature PCMs close to human body temperature should be selected for phase-change clothing cooling materials to avoid the problem of excessive cooling caused by too low phase-change temperature, which makes people feel uncomfortable or the cooling effect is poor. At the same time, from the perspective of the weight of phase-change cooling clothing, solid-gas, and liquid-gas phase-change materials change their volume greatly during use and usually require containers for packaging, which is not easy to use on clothing. PCMs used for clothing heat dissipation should be efficient, safe, and practical. Therefore, polymers, paraffin wax, and hydrogels are commonly used PCMs in phase change cooling clothing.

5. Microchannel heat exchanger

Microchannel heat exchanger (MCHE) has the potential to be used in heat dissipation vests for the human body due to its compact structure, high heat transfer efficiency, small size, and uniform heat dissipation.

A microchannel heat exchanger is a heat exchanger that uses tiny channels to achieve efficient heat transfer. Its typical hydraulic diameter is usually less than 1 mm. When the fluid flows in the microchannel, the heat transfer boundary layer is very thin, so the heat transfer efficiency is significantly improved. Relevant literature points out that the convective heat transfer coefficient of a microchannel heat exchanger is 50% to 100% higher than that of a traditional heat exchanger, and the heat transfer per unit volume far exceeds that of a traditional heat exchanger [8].

5.1. Feasibility analysis

The compact structure and efficient heat dissipation characteristics of microchannel heat exchangers make them very promising for use in wearable devices. For example, by embedding a microchannel heat exchange unit inside a vest, the coolant flows in the microchannel and can quickly remove the heat from the surface of the human body.

Modern manufacturing technologies (such as micromachining technology and photolithography technology) have enabled the mass production of microchannel heat exchangers, which enables the application of microchannel heat dissipation technology in heat dissipation vests. For example, in fuel cell cooling and precision electronic equipment, microchannel heat exchangers have been widely used to achieve efficient thermal management, which provides a practical basis for their application in heat dissipation vests.

Microchannel heat exchangers do not rely on high-power pump systems, but can achieve effective fluid circulation with the help of small pumps, thereby reducing the energy consumption and operating costs of the vest [8].

5.2. Heat dissipation efficiency

Microchannel heat exchangers rapidly remove heat due to tiny channels where coolant directly contacts the heat source, significantly enhancing convective transfer and reducing thermal resistance [8]. Additionally, even fluid flow prevents local overheating, and low weight benefits space-sensitive applications [9].

5.3. Comfort

The microchannel heat exchanger is lightweight, and its volume and overall weight are lighter than those of liquid cooling. Compared with traditional liquid cooling systems, it can better control the overall weight of the vest and improve the comfort of wearing. For example, in high heat flux density equipment (such as lasers or precision electronic equipment), the microchannel heat exchanger not only improves the heat dissipation efficiency of the equipment but also reduces the overall weight of the system due to its lightweight design.

The microchannel heat exchanger provides strong heat dissipation performance through the circulation of coolant. However, if the coolant temperature is too low, it may cause discomfort to the wearer. Therefore, a reasonable temperature control system (such as automatic adjustment of the coolant temperature) should be designed to improve the comfort of wearing [8].

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6. Conclusion

This paper discusses the application of heat dissipation technologies such as liquid cooling technology, phase change materials (PCM) and microchannel heat exchangers in wearable cooling vests, and analyzes the feasibility and wearing comfort. Liquid cooling technology has efficient heat dissipation performance and is suitable for workers and professionals who need to be in high-temperature environments for a long time. However, its weight and complexity still need to be optimized in future designs. Phase change materials have excellent latent heat storage capacity, but their challenges in the preparation process and breathability limit their large-scale application. Microchannel heat exchangers have the advantages of compact structure, lightweight and high heat dissipation efficiency, providing a new solution for portable cooling vests, especially for scenes with high requirements for heat dissipation performance and wearing comfort, but the design of efficient and comfortable microchannel structures is also complex. At the same time, there are many heat dissipation technologies and methods that are not covered in this article. Future work should focus on optimizing vest portability and comfort, including intelligent temperature control. With multidisciplinary collaboration, portable cooling vests will offer safer, more comfortable, and efficient support in high-temperature operations.

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