

A Review on the Physical Mechanism of Passive Heat Dissipation Materials for Building Energy Conservation

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Abstract: This paper systematically reviews the mainstream physical mechanisms of passive heat dissipation materials in the field of building energy conservation, and analyzes the physical principles, material systems, and performance characteristics of the three technical paths of radiation cooling, evaporative phase change cooling, and thermal conduction regulation cooling; summarizes the research progress of various passive heat dissipation materials in building envelopes such as roofs and exterior walls, compares the advantages and inherent shortcomings of different heat dissipation mechanisms; at the same time, it summarizes the current technical bottlenecks from the perspectives of environmental adaptability, long-term service durability, preparation cost, and building conditions adaptation; finally, in response to the actual application requirements of engineering, it looks forward to the future development direction of passive heat dissipation materials, aiming to provide theoretical references for the research and development of new passive heat dissipation materials, the construction of multi-mechanism composite systems, and the integrated application of building envelopes.

Keywords: passive heat dissipation; radiation cooling; evaporation cooling; thermal physical mechanism; building envelope structure

1. Introduction

Under the background of global climate warming, hot weather occurs frequently, and the demand for indoor cooling in buildings continues to increase [1]. According to relevant statistics, the energy consumption during the operation of buildings accounts for a relatively high proportion of the total energy consumption of the society [2]. Among them, the energy consumption for air conditioning cooling in summer occupies a large proportion of the building operation energy consumption. Traditional compressor-type air conditioners belong to active cooling methods, which consume a large amount of electricity and release a large amount of waste heat into the urban environment, further aggravating the urban heat island effect and forming a vicious cycle. Therefore, developing passive cooling technologies that do not consume electricity and reducing the cooling load of

buildings have become a hot research direction in building energy conservation.

Passive cooling technology differs from active cooling methods such as fans and air conditioners. It does not rely on external energy sources but instead uses the physical processes of the materials themselves to transfer and dissipate heat, transferring the heat accumulated in the building envelope to the external environment, thereby reducing the temperatures of the walls and roofs and reducing the heat transferred into the interior. Currently, passive cooling encompasses multiple implementation paths, and the corresponding physical mechanisms for each path are completely different, with significant differences in requirements for material composition, microstructure, and usage environment [3-4]. Radiant cooling uses the infrared transparent window of the atmosphere to radiate heat to the cosmic cold source; evaporative cooling achieves cooling through the heat absorption of water phase change; thermal conduction regulation realizes the redistribution of heat by optimizing the heat conduction path.

In recent years, a large amount of research has been conducted both domestically and internationally on passive cooling materials, resulting in the development of various forms of cooling materials such as coatings, films, and porous plates. However, most of the research focuses on the performance testing of materials under laboratory conditions, lacking a systematic review for real-world building conditions [5]. Factors such as cloudy and rainy weather, dust accumulation, and significant fluctuations in temperature and humidity can significantly affect the actual cooling effect of passive cooling materials. Materials with a single mechanism often have obvious limitations in application and are difficult to directly meet the long-term usage requirements of building projects. Based on this, this paper focuses on the application scenarios of building energy conservation, conducts a review of the physical mechanisms, material systems, application status, and existing problems of various passive cooling materials, summarizes the existing research results, analyzes technical pain points, and provides references for subsequent related research and engineering implementation.

2. The Core Physical Mechanism of Passive Heat Dissipation Materials

2.1. Radiation Cooling Mechanism

The physical basis of radiation cooling is the law of heat radiation exchange. All objects with a temperature above absolute zero will emit infrared electromagnetic waves. The Earth's atmosphere has an infrared transparent window ranging from 8 to 13 μm , through which infrared radiation in this wavelength band can pass through the atmosphere and directly project onto the cosmic cold source with a temperature close to 3K, thereby achieving heat dissipation to outer space and achieving the cooling effect. According to the working time, it can be divided into night-time radiation cooling and daytime radiation cooling. At night, there is no solar radiation, and the material only needs to have a high infrared emissivity in the 8-13 μm wavelength band to radiate heat and achieve cooling. The technical threshold is relatively low. While daytime radiation cooling needs to simultaneously achieve two key optical performances: first, to achieve high reflection in the 0.3-2.5 μm solar light wavelength band to minimize solar absorption and avoid the material being heated by the sun; second, to maintain a high infrared emissivity in the 8-13 μm atmospheric window to continuously radiate heat. Only when both performances are met can the cooling effect below the ambient temperature be achieved in the sunlight direct exposure environment. Currently, the radiation cooling material system is mainly divided into inorganic base composite materials and polymer base composite materials [6]. The inorganic system often selects silica, titanium dioxide, etc. as functional fillers, using the optical scattering characteristics of the particles to reflect solar light, and relying on the intrinsic infrared vibration of the silicon-oxygen bond to achieve high infrared emission. The polymer system mostly uses polyvinylidene fluoride, polymethyl methacrylate, etc. as high molecular substrates, regulating the optical response through the microscopic porous structure. The material product forms include films, sprayed coatings, prefabricated panels, etc., which can be adapted to building roofs, exterior walls, etc. Radiation cooling technology has inherent environmental limitations. Water vapor and water droplets in clouds strongly absorb the 8-13 μm infrared wavelength band, and cloudy, rainy weather will block the radiation heat dissipation channel, significantly reducing the cooling performance. In outdoor building environments, dust and sand will adhere to the material surface, reducing the solar reflectivity, and the cooling effect gradually deteriorates after long-term use. In addition, ultraviolet aging will damage the microscopic structure of the high molecular substrate and change the optical properties, restricting long-term service.

2.2. Evaporation Phase Change Heat Dissipation Mechanism

The physical essence of evaporative cooling is the heat absorption during the liquid-gas phase change of water.

During the process of water changing from liquid to gas, it absorbs a large amount of latent heat of phase change and takes away heat from the solid surface, achieving surface cooling. Evaporative cooling materials used in building scenarios are generally porous hydrophilic materials, which complete the entire process of water storage, moisture transmission, and water vapor diffusion through internal interconnected pores. Rainwater or artificially replenished water is stored inside the material pores, and the environmental air flow drives the evaporation of water within the pores, absorbing the heat on the surface of the enclosure structure and reducing the temperature of the wall or roof [7]. The greatest advantage of evaporative cooling is the large cooling amplitude. In high-temperature and dry environments, it can achieve considerable temperature reduction. This technology does not require special optical regulation, and the raw materials are mostly inexpensive and readily available. However, the performance of evaporative cooling is highly dependent on the relative humidity of the environment [8]. When the air humidity is high, the water vapor partial pressure in the air approaches saturation, and the driving force for water evaporation is insufficient, resulting in a significant reduction in the cooling and temperature reduction effect. At the same time, evaporative cooling must continuously supply water, mainly relying on natural rainfall for replenishment. In the absence of rainfall for a long time, the water in the pores is depleted, and the cooling function disappears directly. Common evaporative cooling building materials include porous ceramics, modified concrete, and hydrophilic porous fibers. Repeated dry-wet cycles of water will bring many engineering problems: water evaporation dissolves salt substances, causing surface salt precipitation and whitening; long-term dampness in the pores is prone to the growth of mold; repeated absorption and loss of water will cause material swelling and contraction, resulting in cracking and damage of the base. These problems limit the direct use of evaporative cooling materials as building exterior cladding. Currently, they are more commonly used in roof systems in arid regions.

2.3. Thermal Conduction Mechanism for Regulating Heat Dissipation

Thermal conduction regulation is based on Fourier's law of heat conduction and achieves heat transfer by adjusting the thermal conductivity of materials. It can be divided into two directions: high thermal conductivity for heat output and insulation to prevent heat transfer. The idea behind high thermal conductivity materials is to enhance the heat conduction capacity of the enclosure structure, quickly transferring the heat accumulated in the wall volume to the outer surface, and then combining with other cooling methods to dissipate the heat into the environment. Insulation materials rely on low thermal conductivity to block the transfer of high-temperature from the outside to the interior. It is worth noting that relying solely on thermal conduction regulation cannot transfer the heat within the building system to the

external environment; it can only achieve the redistribution of heat within the building components. High thermal conductivity materials can only accelerate the heat reaching the outer surface. If there are no dissipation paths such as radiation or evaporation on the outer surface, the heat will still accumulate in the building system and cannot achieve true passive cooling. Therefore, thermal conduction regulation is rarely used as a standalone passive cooling method; it is mostly used as an auxiliary part of a composite cooling system. In the composite system, high thermal conductivity fillers (such as graphite, boron nitride, etc.) are added to the radiation cooling coating or evaporation porous matrix to improve the efficiency of heat transfer within the material and reduce heat accumulation within the material [9]; low thermal conductivity porous substrates are used to prevent heat from reversing and entering the building interior, and work in synergy with the main cooling mechanism to enhance the overall cooling effect.

3. Current Application Status and Comparative Analysis of Various Passive Heat Dissipation Materials in Construction

3.1. The Current Application Status of Radiation Cooling Materials in Building Construction

Radiation cooling materials are the most extensively studied area in the field of passive cooling for buildings. They come in various forms, such as sprayable coatings, flexible films, and prefabricated decorative panels, which can be adapted for both new buildings and renovations of existing ones. Roofs are the primary application scenarios for radiation cooling materials, as they receive intense solar radiation and have no strict constraints from exterior decorative colors. Numerous practical tests have shown that radiation cooling roofs can effectively lower the surface temperature of the roof, reduce heat conduction to the interior, and reduce the building's air conditioning load on clear days [10]. However, for high-performance radiation cooling materials during the day, the micro-nanometer filler preparation process is complex, and the cost for large-scale engineering procurement is relatively high. Additionally, there are limitations in the application of building exteriors, as most efficient radiation cooling materials are white, and some building exteriors have color requirements. Colorful radiation cooling coatings will absorb some sunlight, directly weakening the cooling performance. Anti-fouling and weather resistance remain the core pain points for the engineeringization of radiation cooling materials. After being exposed to the outdoors for several months, accumulated dust will significantly reduce the cooling performance. Self-cleaning modification is currently an important research direction.

3.2. The Current Application Status of Evaporative Cooling Materials in Construction

Evaporative cooling materials are cost-effective and have great potential for application in the arid regions of northwest China [11-12]. The porous evaporative roof

can store water after rainfall and rely on water evaporation to achieve cooling during hot and dry weather. However, in the humid and rainy areas of southern China, the air humidity is high and the evaporation efficiency is low, resulting in limited cooling benefits. The shortcomings of evaporative cooling material engineering are prominent: it is dependent on water resources and loses its cooling ability during consecutive drought periods; the dry-wet cycle leads to problems such as salt precipitation, mold growth, and substrate aging, and currently, it is rarely directly used as an exterior wall finish. Existing research mostly sets the evaporative material as a roof interlayer or sets up an independent water replenishment system to avoid the problem of exterior mold growth.

3.3. Research on Multi-Mechanism Composite Heat Dissipation System

All single-mechanism passive heat dissipation materials have significant shortcomings. Combining multiple physical mechanisms is an important approach to improving environmental adaptability. By combining the radiation cooling layer with the porous evaporation layer, when there is no moisture on a sunny day, it relies on infrared radiation for heat dissipation; after rainfall, the pores store water and the evaporation and phase change absorb heat, and the dual mechanisms work together to cool down. At the same time, a high thermal conductivity intermediate layer is introduced to accelerate the transfer of heat from the base material to the heat dissipation interface. The multi-mechanism composite system can broaden the applicable range of temperature and humidity, taking into account different working conditions on sunny days and after rainfall. However, the composite system also brings new problems. The interface compatibility of multiple layers, the interlayer bonding strength, and the mismatch in aging rates between different materials all require further research. Currently, most multi-mechanism composite passive heat dissipation materials are still at the laboratory research stage, and there are relatively few complete technologies for building envelope structures.

4. The Current Key Issues

At present, the performance data of many passive cooling materials are obtained under ideal laboratory conditions, with controlled temperature and humidity and no interference from dust accumulation. However, the real environmental conditions in buildings are complex and changeable: cloudy, rainy, dusty, with large temperature differences between day and night, which significantly reduces the cooling capacity of the materials [13]. Many materials have excellent cooling effects in laboratory conditions, but the actual measured cooling effects are greatly reduced in the field. For different climate zones, there is a lack of unified testing and evaluation methods, making it difficult to compare the actual engineering performance of different materials horizontally.

Passive cooling materials applied to building exteriors

and roofs need to endure long-term exposure to solar ultraviolet radiation, rain erosion, temperature variations between day and night, and dust deposition [14]. Polymer-based radiation cooling coatings undergo aging due to long-term ultraviolet exposure, with structural damage and optical performance degradation; evaporative materials undergo repeated dry-wet cycles, with prominent risks of salt precipitation, mold growth, and matrix cracking. Currently, most studies only conduct short-term performance tests, lacking data from outdoor aging tests over several years, which limits the promotion of these materials in construction projects.

High-performance daytime radiation cooling materials require precise control of micro-nano structures, with high costs for raw materials and preparation processes [15]. Large-scale building applications face significant economic pressure. It is difficult for ordinary construction projects to bear the high cost. Developing low-cost fillers and simple preparation processes, balancing performance and cost, is a necessary condition for realizing engineering implementation.

A large number of existing literature focuses on the modification and preparation of materials themselves, and the coupled simulation of the complete heat transfer process of building walls and roofs is relatively limited, with relatively limited on-site measurements. How passive cooling materials can be integrated with the insulation layer and waterproof layer of the building envelope, and what type of passive cooling scheme is suitable for different climate regions, and related system research is still relatively lacking.

5. Summary and Outlook

Passive heat dissipation materials rely on physical mechanisms such as radiation cooling, evaporation phase change, and heat conduction regulation to lower the temperature of building envelope structures without consuming external energy. This is a promising technical path for building energy conservation and carbon reduction. Radiation cooling can achieve passive heat dissipation throughout the day, but it is significantly affected by clouds and dust accumulation; evaporation phase change has strong cooling capacity, but it highly depends on moisture and low humidity environments; heat conduction regulation is generally used as an auxiliary means to optimize the heat transfer within the system. Each single mechanism material has its environmental application boundaries, and the multi-mechanism composite is an important development direction.

For practical applications in construction engineering, subsequent research can focus on the following aspects: First, develop new passive heat dissipation materials that take into account heat dissipation performance, weather resistance, anti-fouling, and low cost, simplify the preparation process, and reduce the engineering application cost; Second, deepen the research on multi-mechanism composite passive heat dissipation systems, coordinate the compatibility between different functional layers, and expand the application range of materials in

different temperature and humidity conditions; Third, strengthen on-site measurement and numerical simulation in different climate zones for buildings, establish a material-closure structure coupled heat transfer model, and promote the integrated design of passive heat dissipation materials and building components; Fourth, establish a performance evaluation system for passive heat dissipation materials in building scenarios, standardize test conditions, promote this technology from the laboratory to actual engineering, and facilitate the development of green and low-carbon buildings.

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