

Research Progress on Energy-saving Passive Cooling Materials

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Abstract: The worsening energy shortage, especially in the context of global warming, has led to a significant proportion of refrigeration energy consumption. Therefore, it is necessary to develop energy-saving passive cooling materials. Passive cooling materials can be divided into two types: traditional passive cooling materials and passive radiation cooling materials, each with its own advantages and disadvantages. Foam plastics and silver paint are often used in traditional passive cooling materials, and passive radiation cooling materials have also become a research hotspot. Atmospheric transparent windows are an important foundation for radiative cooling, and suitable polymer and inorganic materials can be used for passive radiative cooling. Proper modification of coatings can also have a passive radiation cooling effect. Meanwhile, passive cooling materials have enormous potential for application in various fields of life and production. In addition to the most common building cooling, large-scale chemical production equipment, solar cells and other facilities are no exception.

Keywords: Passive cooling, Radiation cooling, Coatings, Application value

1. Introduction

The shortage, price volatility and increasing demand of energy has led to energy crises[1] globally. And as the global warming intensifies, refrigeration has also become an important component of energy consumption. Taking China as an example, China is the country with the highest energy consumption in the world, with building energy consumption accounting for over 20% of total energy consumption[2], and refrigeration energy consumption accounting for almost half of building energy consumption. Refrigeration electricity consumption accounts for over 15% of the total electricity consumption in society[3]. Hence, the development of new energy and cooling modes is of great significance and urgent need for reducing indoor temperature and solving building energy consumption problems.

A green, environmentally friendly, and energy-saving passive cooling material is crucial for solving the above problems. The passive cooling materials have a wide range of applications. Besides the traditional passive cooling material, passive cooling materials based on the principle of passive radiation cooling are emerging. Passive radiative cooling is the use of atmospheric transparent windows to send its own thermal radiation into outer space to achieve a temperature lower than the ambient temperature[4]. In the field of radiation cooling materials, inorganic multilayer radiation cooling materials, polymer materials, coatings, etc. have all received attention from researchers.

2. Traditional passive cooling materials

Traditional passive cooling materials mainly achieve cooling effects through the principles of insulation or reflection. Foamed plastic and silver paint are typical examples[5].

2.1. Foamed plastic

Foamed plastic, also commonly referred to as expanded plastic or polystyrene foam[6], represents a versatile and lightweight material characterized by its cellular structure, and one of the primary advantages of foam plastic is its excellent thermal insulation capabilities. The gas-filled cells act as an effective thermal barrier and the cellular structure of foam plastics also minimizes convective heat transfer.

In order to optimize the thermal insulation performance of foamed plastics, new processes need to be developed. Liu's team[7] has made a new type of PDA/GO/PUF polyurethane foam. The thermal insulation performance of PDA/GO/PUF was characterized by infrared thermography and combustion experiments. The results show that PDA/GO/PUF has more excellent and stable thermal insulation effect than PUF, and there is no droplet phenomenon in the combustion process.

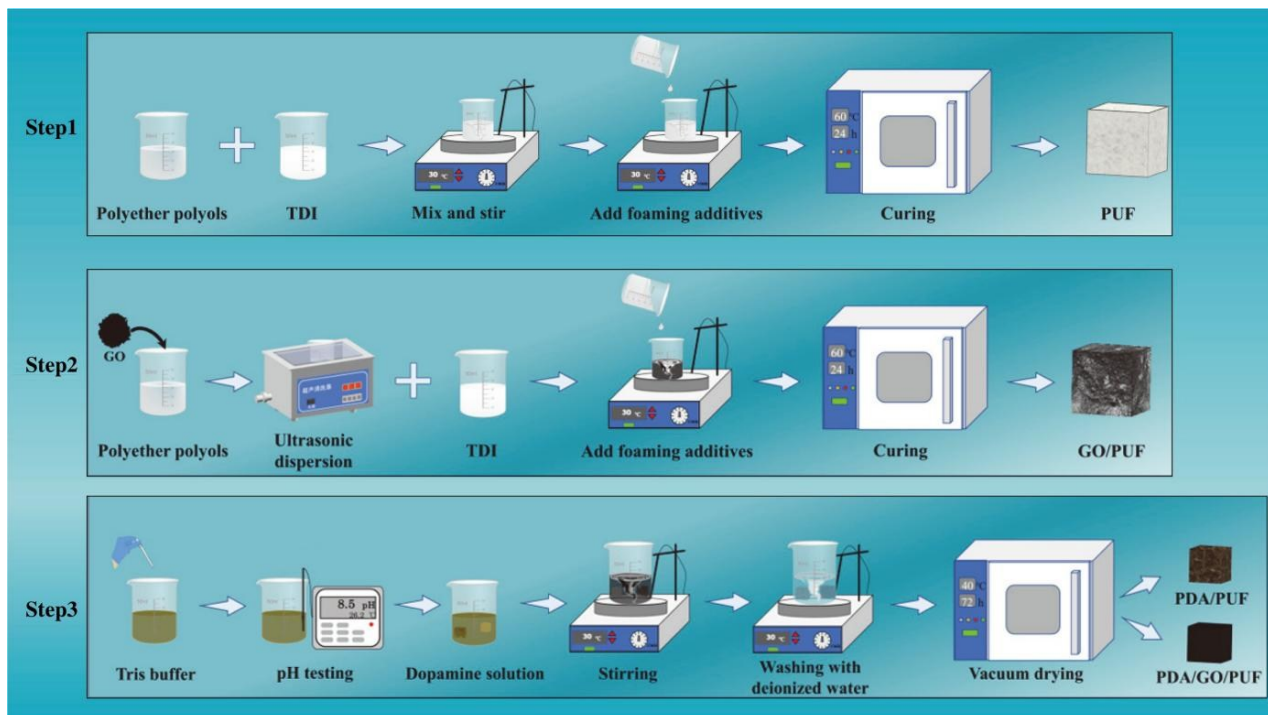


Figure 1: Process flow diagram for the fabrication of PDA/PUF and PDA/GO/PUF polyurethane foams[7].

2.2. Silver paint

Silver powder paint is a type of paint that contains silver or aluminum powder as its main pigment. The pigment gives the paint a metallic, shiny appearance and also provides it with unique properties such as heat reflection. The principle of reflection for cooling in silver powder paint is based on the high reflectivity of the metal. Silver and aluminum have a reflectivity of over 95%, which means it can reflect a large amount of incident radiation, including heat. When silver powder paint is applied to a surface, it forms a layer that reflects heat radiation from the sun or other heat sources. This reflection reduces the amount of heat that is absorbed by the surface, thereby lowering its temperature.

The modification of silver powder paint is also an important issue. Alcohol resistant silver powder paint can be formulated by selecting thermoplastic acrylic resin, acetate fiber, solvent, silver powder, and additives[8]. Water-Dispersible CAB-Modified Thermoplastic Acrylic Resin (WCAB-AC) can be used to improve the appearance of silver powder paint and reduce its TVOC content[9].

3. Passive radiation cooling materials

Although foam plastic and silver paint have significant heat insulation and cooling effect, once the heat enters the internal space, even if the external heat is weakened, the internal temperature is still difficult to reduce. Radiation cooling materials can effectively compensate for the above-mentioned defects. The Earth's atmosphere has a highly transparent window in the infrared wavelength range of 8-13 μm , where the radiance of the atmosphere is very weak, known as the atmospheric transparency window[10]. Passive radiation cooling materials fully utilize the effects of thermal radiation[11], atmospheric transparency windows, and broadband emission[12] to achieve energy-free cooling below ambient temperature.



Figure 2: Schematic diagram of Earth's heat exchange[13].

3.1. Polymer materials

Typical high molecular weight polymers such as polymethylpentene (TPX)[14], polydimethylsiloxane (PDMS)[15,21], polymethylmethacrylate (PMMA)[16], polyvinylfluoride (PVF)[17,18], polyethyleneoxide (PEO)[19], etc. have high emissivity in atmospheric transparent windows. This is because these polymers contain C-O, C-N, C-Cl, C-F bonds, etc., and the absorption vibration peaks of these chemical bonds are within the 600-1500 cm^{-1} atmospheric window[20].

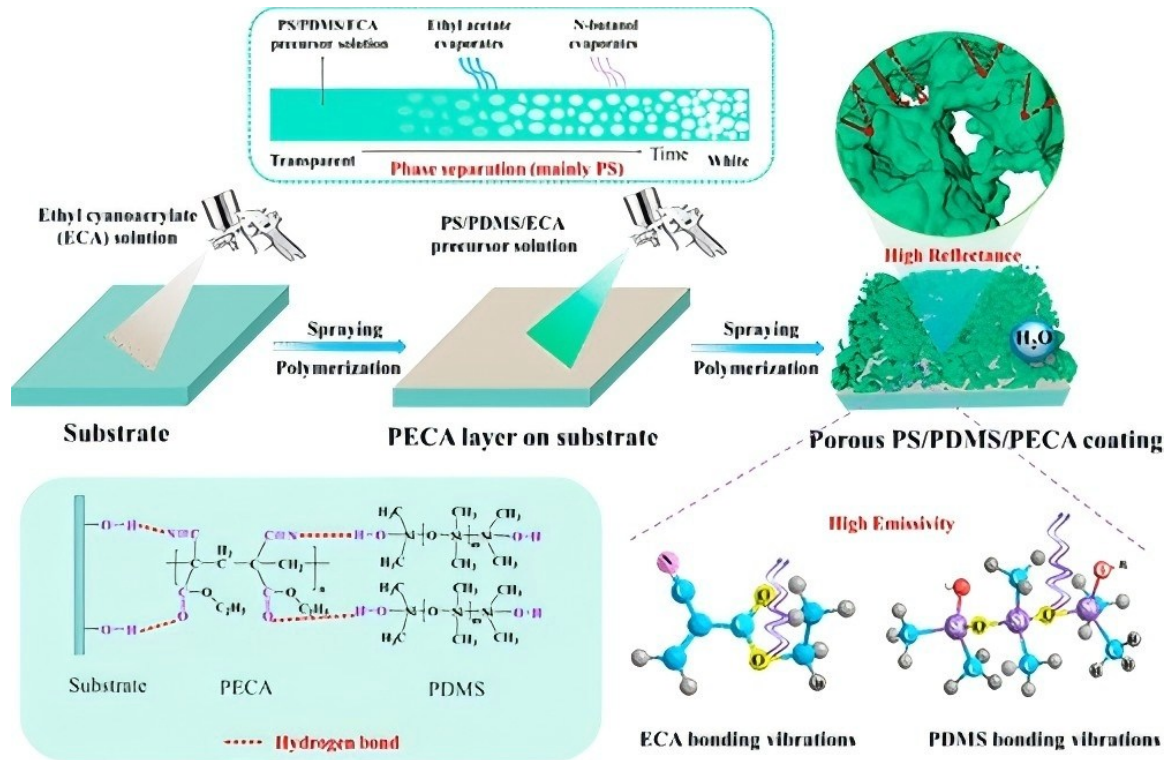


Figure 3: Schematic of the preparation of the PS/PDMS/PECA coating through spraying[21].

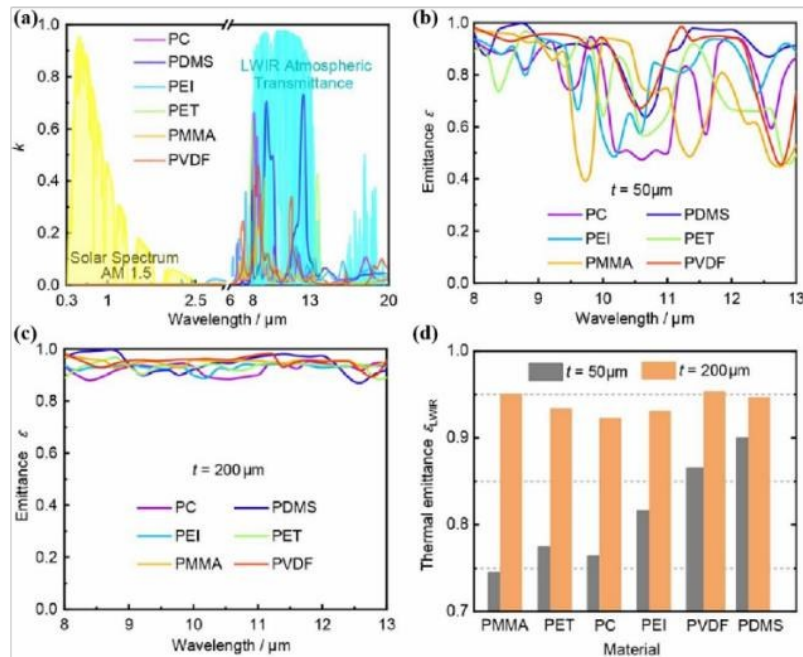


Figure 4: (a) Extinction coefficient of polymers; The emission spectra of polymer films at thicknesses of (b) $50 \mu\text{m}$ and (c) $200 \mu\text{m}$; (d) Summary of emissivity of polymer films at different thicknesses[22].

Chen et al.[22] studied the emissivity of various polymer films at different thicknesses, as shown in Figure 3. At a thickness of $200 \mu\text{m}$, numerous polymer materials can achieve high emissivity (>0.9), providing the possibility for nighttime radiative cooling. In addition, the extinction coefficient k of these polymers in the solar wavelength range is almost zero, indicating that they have very little ability

to absorb sunlight. But these film materials are basically transparent, and a large part of the sunlight will pass through the film, which is not conducive to radiation cooling during the day. Usually, the ability to reflect sunlight is improved by introducing porous structures or high solar reflective substrates such as silver, aluminum, and other metals. Zhou et al.[15] coated PDMS on an Al plate and designed a spectral selective structure to suppress solar input, control thermal emission divergence, and achieve a temperature reduction of up to 11 °C by utilizing the high selective emission of PDMS and the high solar reflection of the Al plate.

3.2. Inorganic materials

Common inorganic materials, including Al_2O_3 [23], SiO_2 [24], Si_3N_4 [25], etc., also exhibit bond absorption vibrations within atmospheric transparent windows, making them equally capable of achieving radiative cooling, with excellent weather resistance.

The effect of radiative cooling can be achieved by combining photonic structural materials with metal substrates. Photon structures enhance the selective emissivity of materials, while metal substrates enhance the solar reflectivity. Chae et al.[27] designed a radiation cooling material with a multi-layer structure of inorganic materials, namely Al_2O_3 , Si_3N_4 , and SiO_2 , and exhibited high selective emission in the 8-13 μm region, as shown in Figure 6. By using an evolutionary algorithm based particle swarm optimization method, the stacking order and thickness of each layer were optimized to maximize the radiation in the 8-13 μm region and minimize the cooling temperature. The average emissivity of the inorganic radiation cooler in the range of 8-13 μm is 87%, and the average absorptivity in the solar spectral region is 5.2%. Compared to the internal ambient temperature under direct sunlight during the day, inorganic radiation cooling materials can reduce the temperature by 8.2 °C.

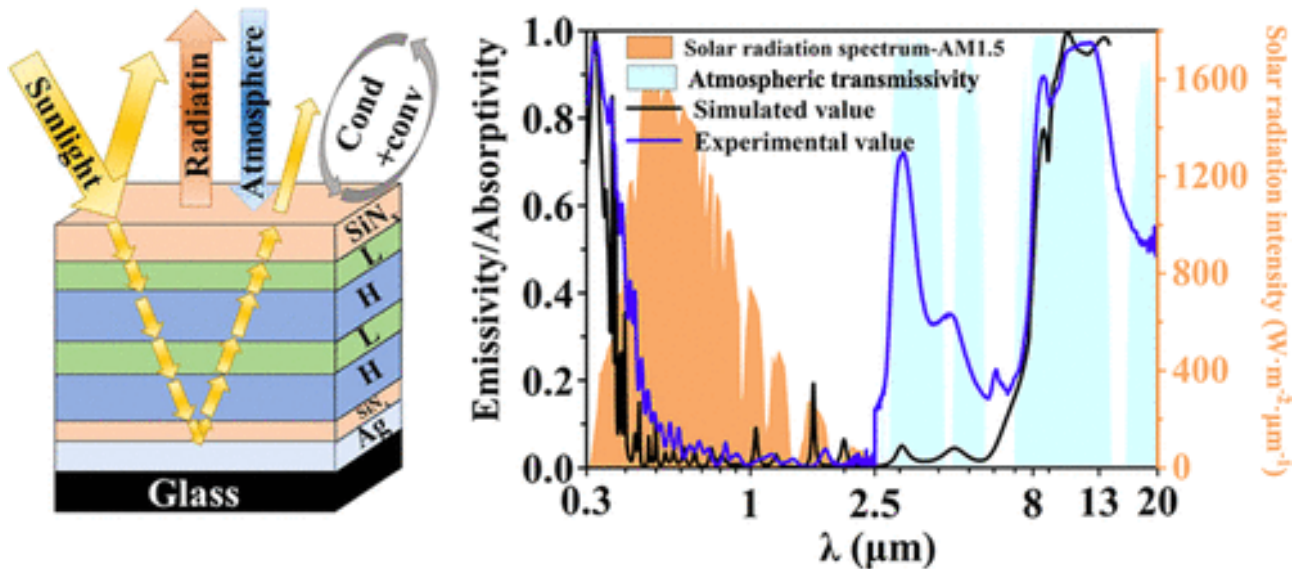


Figure 5: Inorganic Multilayer Film with High Infrared Selective Emission Enhanced by SiNx for Daytime Radiative Cooling[26].

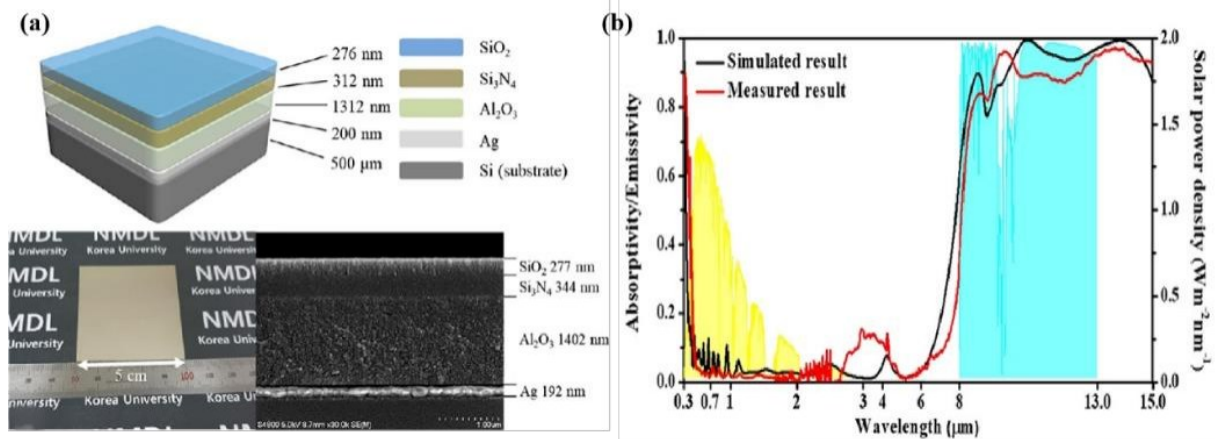


Figure 6: (a) Structure of inorganic radiation cooling materials; (b) Absorption/emission spectra of radiative cooling materials[27].

3.3. Coatings

Although polymer materials and inorganic multilayer radiation cooling materials have good cooling performance, these radiation cooling materials still have their own defects. Polymer based radiative cooling materials typically require a metal reflective layer or porous structure to reflect sunlight in order to achieve effective daytime cooling and achieve energy-saving and emission reduction goals, and cannot be directly applied to building exterior walls. The process of inorganic multi-layer radiation cooling materials is complex and has weak mechanical strength. Compared to the above materials, coatings have significant advantages.

In terms of composition, coatings are composite materials composed of optical scatterers embedded in polymers. In the current cooling coating industry, rutile TiO₂ is the preferred white pigment. The high refractive index[28] of TiO₂ nanoparticles relative to polymer materials enables them to scatter sunlight more effectively than an equal amount of other white pigments, making TiO₂ cost-effective. The study[29] has optimized the TiO₂ particle size to enhance scattering and approach the reflection limit, but polymer resins also exhibit near-infrared absorption. Even after optimization, the average reflectivity of the best TiO₂ based coatings in the solar spectrum is only about 90%. Cannot generate cooling below ambient temperature in strong sunlight. Therefore, it is imperative to further improve the radiation cooling performance of coatings.

A double-layer passive radiation cooling coating scheme has been proposed, in which the topcoat is a coating that combines high reflective radiation and scattering performance, mainly using hollow SiO₂, ZrO₂ with high refractive index and wide bandgap as fillers, and water-based fluorocarbon resin with strong weather resistance as resin. Compared to solid structures, the design of fillers as hollow structures increases the air filler interface to enhance light scattering behavior. When light propagates, a portion of the light is reflected back to the outside of the material, thereby improving cooling performance.; The primer serves as the insulation layer, mainly using low thermal conductivity materials as fillers and water-based acrylic resin with strong adhesion as the resin. The topcoat and primer materials both emit broadband radiation in the atmospheric window area, providing excellent outward heat radiation capability for the coating. The coating was applied to the surface of a simulated house, and the internal temperature of the house was on average 5.2, 6, and 11 °C lower than that of commercial coatings, titanium dioxide fluorocarbon coatings, and blank houses, respectively, as shown in Figure 8. The actual cooling effect was excellent[30].

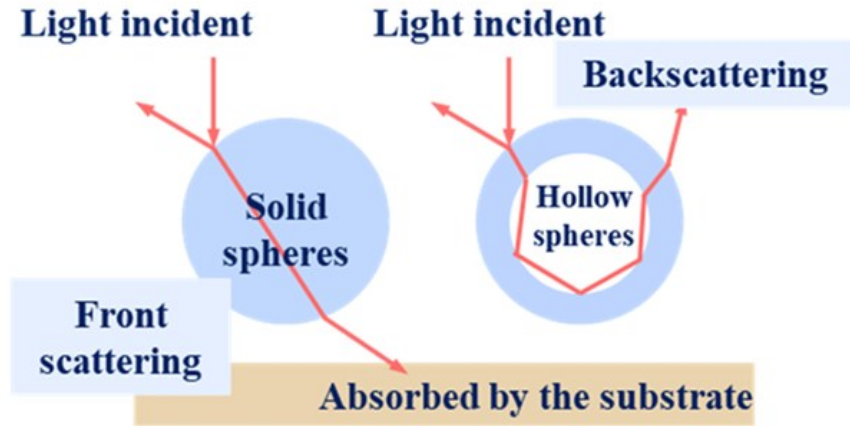


Figure 7: Comparison of hollow and solid fillers under light conditions[31].

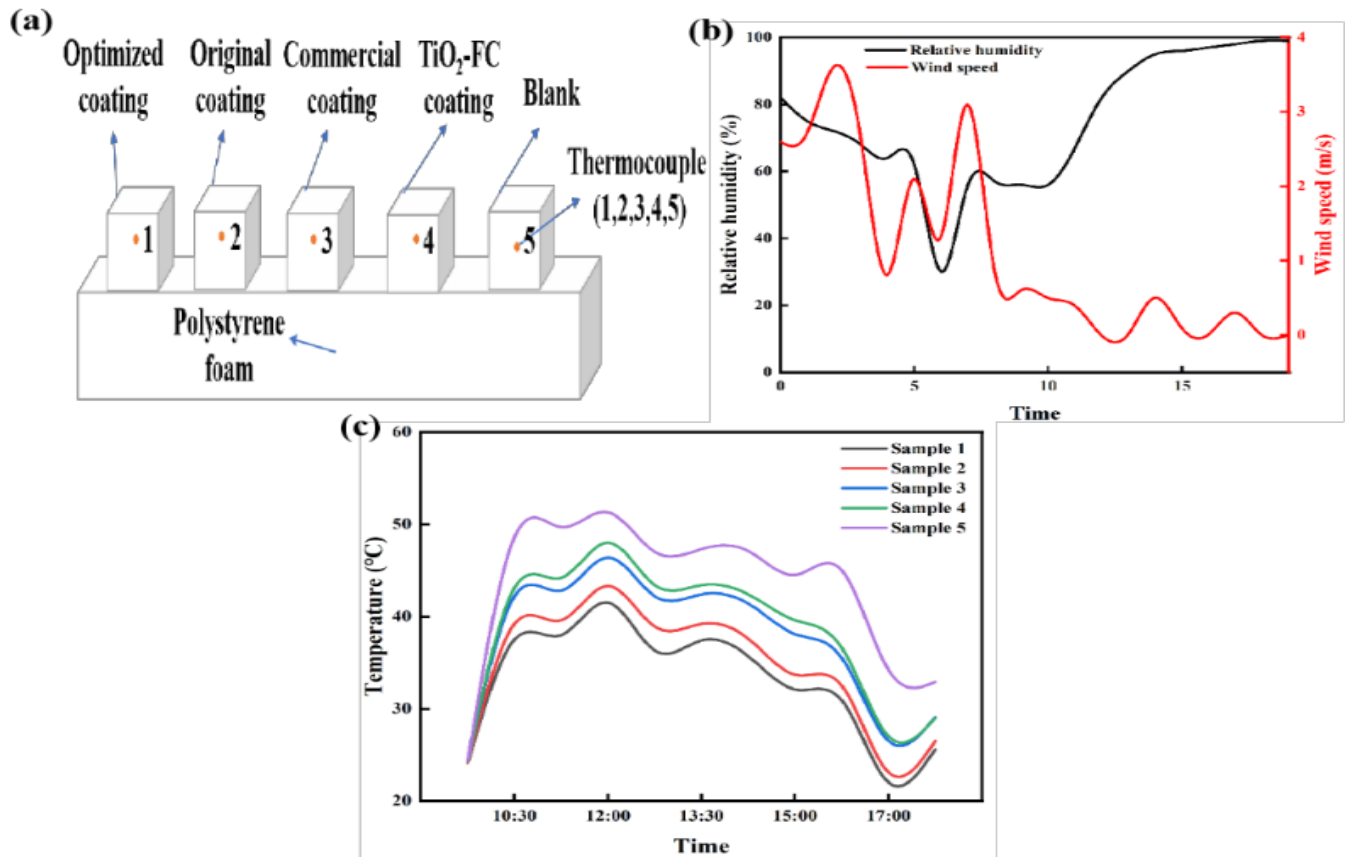


Figure 8: (a) Model diagram of simulated house testing device; (b) Test the environmental humidity and wind speed on the day of testing; (c) Five internal temperature test chart of the house.

4. Applications

4.1. Buildings

Most of the time, humans are active inside buildings, and heating, ventilation, and air conditioning systems (HVAC), which regulate the ecological conditions inside buildings, consume energy[32].

Therefore, if radiation cooling is used for building temperature control, it is expected to save a huge amount of energy consumption, which is of great significance for the global energy-saving and emission reduction landscape.

Firstly, radiation cooling materials can be used on the roofs of buildings, which are not only the places where temperatures are most likely to rise during the day due to direct sunlight, but also the places where effective radiation cooling can be carried out at night directly facing outer space; Meanwhile, radiation cooling materials can also be used for building exterior walls, with coatings applied to achieve radiation cooling effects. Secondly, radiation cooling facilities can be combined with air circulation systems and water circulation systems to regulate the temperature of the entire building[33]. Fan's team[34] combined a radiation cooling film that can work during the day with a water circulation system to develop a fluid cooling panel device, as shown in Figure 9. This device uses radiation cooling to lower the water temperature below room temperature, and then circulates the water throughout the building to achieve cooling of the building. At a water flow rate of $0.2 \text{ L}/(\text{m}^2 \cdot \text{min})$, At a radiation power of approximately $70 \text{ W}/\text{m}^2$, the device achieved a cooling effect of reducing the temperature of the circulating water to 5°C below the ambient temperature.

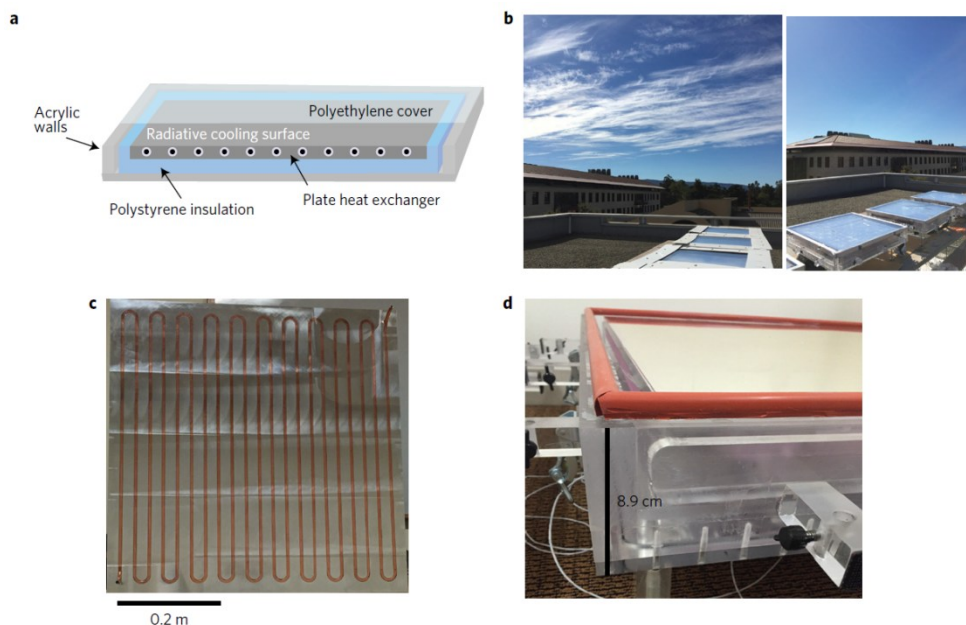


Figure 9: Radiative cooling system built by Fan's group, (a)the schematic diagram, (b,c,d) experimental setup[34].

4.2. Large scale chemical production equipment

In the process of chemical production, a large amount of heat dissipation is required during raw material storage, reaction, pipeline transportation, etc., and radiators are often used. Radiators are also widely used in various industries such as light industry, construction, machinery, textile, printing and dyeing, electronics, food, starch, medicine, metallurgy, painting, etc. Heat transfer and exchange are essential key designs in chemical production, and accelerating heat dissipation is a key issue in chemical production. Passive cooling materials have low cost and wide application scenarios, and can be coated on the surfaces of storage tanks, pipelines, and reactors to continuously reflect and radiate heat, accelerating heat dissipation and saving a lot of energy in industrial production.

4.3. Solar panels

Solar cells use the photovoltaic effect to directly convert solar energy into electrical energy, with a conversion efficiency generally between 12-20%. Most of the remaining solar energy is converted into heat, causing the temperature of the solar panel to rise. This heating effect will have adverse effects on the efficiency and lifespan of solar cells.

According to statistics, for solar cells made of crystalline silicon, for every 1 °C increase in temperature, the energy conversion efficiency will relatively decrease by about 0.45% [35]. If a radiation cooling film that is transparent in the solar band and highly absorbing in the mid infrared band is added to the surface of the solar panel, it can reduce the temperature of the panel and improve its performance. The surface temperature of solar panels in work can reach up to 60 °C, much higher than the ambient temperature. Therefore, in radiation cooling for solar cells, broad-spectrum radiation devices with high emissivity in the entire mid infrared band can be used. This not only allows the heat generated by the solar panel to dissipate at multiple wavelengths, but also reduces the manufacturing cost of radiation cooling materials [36].

5. Conclusion and Future Scope

This article elaborates on the necessity of developing passive cooling materials, the types and applications of passive cooling materials, and combines our team's research results, intended to provide direction for the research and development of passive cooling materials. It elaborates on the necessity of developing passive cooling materials, the types and applications of passive cooling materials, and combines our team's research results, intended to provide direction for the research and development of passive cooling materials.

The current passive cooling materials still have problems such as high raw material costs, easy agglomeration of fillers, material cracking, and difficulty in maintaining insulation in winter. Hoping that in the future, with the further development of science and technology, these problems can be effectively solved.

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