Article ID 42402131

Radiative Sky Cooling: Introduction and Prospective application in Dairy Industry

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Abstract

Radiative sky cooling is a natural phenomenon where the surface of a material cools by emitting thermal radiation into the atmosphere rather than through conduction or convection. This phenomenon occurs because the surface of a material emits infrared photons that travel through the atmosphere and are absorbed by the cooler sky. The process relies on the temperature difference between the surface and the atmosphere to cool the surface through thermal radiation. This cooling method has been investigated as a potential solution for passive cooling of buildings and structures as it could reduce the reliance on air conditioning and other active cooling systems.

Introduction

As the world faces increasing energy shortages and environmental issues such as global warming, there is a growing need for alternative cooling technologies that are robust and environmentally friendly. With rapid urbanization, population growth, and increased transportation, the demand for cooling is expected to rise significantly by 2050, with projections estimating a demand equivalent to 5.8 EJ in Latin America, China, and India. Radiative sky cooling (RSC) is a promising passive technique that can help address this cooling demand by reflecting and radiating excessive heat (Farooq et al. 2021). In contrast to the current dominant vapor compression-based cooling technologies, RSC offers a sustainable and efficient alternative that reduces heat gain without the massive energy consumption or environmental concerns associated with refrigerants such as hydrofluorocarbons (HFCs) that contribute to global warming.

The concept of radiative sky cooling can be divided into two scenarios: nocturnal (night time) and diurnal (day time). During the night, deep space acts as a heat sink at a temperature close to absolute zero (~3 K), and radiative sky cooling helps to maintain a liveable temperature range on Earth. Recent advancements in materials, particularly metamaterials, have made it possible to dissipate heat during the daytime by maximizing infrared thermal radiation emissions through the atmospheric window while minimizing the absorption of incoming solar radiation. The development of radiative sky cooling materials is not only a significant scientific achievement in materials science but also a milestone in engineering applications. This article discusses the fundamental physics of radiative sky cooling, materials for both night-time and daytime, and their real-world applications.

Material and structure of radiators

Efficient radiative cooling relies on the radiative properties of the radiator, which has led to the development of various materials for nocturnal radiative cooling such as pigmented paints and functional film-coated radiators. However, these materials have limitations during the daytime due to their low reflectivity for solar radiation. Recent advancements in micro/nanomaterials have led to the development of new materials and structures such as photonic structures, nanoparticle-doped materials, and metamaterials for diurnal radiative cooling. Table 1 summarizes commonly used and advanced radiators for both nocturnal and diurnal radiative cooling.

Application developments and prospects

Radiative cooling promises a vital impact with its excellent passive cooling potential, which can be applied in various fields, including energy-efficient buildings, photovoltaic cooling, and energy harvesting. In this section, the application developments and prospects of radiative cooling are summarized and compiled.

Table 1: Commonly used and advanced radiators for both nocturnal and diurnal radiative cooling

Type of material	Material	Author
Nocturnal	Carbon-based nanomaterials, including carbon black, multiwall carbon nanotubes and nano-diamond	Suryawanshi and Lin (2009)
	Amorphous silicon carbide (SiC) nanoparticles in 25 µm thick polyethylene	Gentle and Smith (2010)
	Silicon nitride oxide nanoparticles coating on Al substrate	Gómez-Bombarelli et al. (2016)
Diurnal	Cocoon produced by silk moths	Shi et al (2018)
	Double-layer coating embedded with titanium dioxide and carbon black nanoparticles	Huang and Ruan (2017)
	P(VDF-HFP) polymer along with acetone and water	Mandal et al. (2018)
	ZnO particles into LWIR-transparent HDPE	Torgerson and Hellhake (2020)
	Multilayered photonic emitter by using titanium dioxide (TiO_2) and silicon dioxide (SiO_2)	Jeong et al. (2020)

Energy-efficient buildings

Approximately 40% of the world's energy consumption is attributed to building energy usage, with a significant portion of this energy being utilized for indoor thermal management through traditional HVAC systems (Omer et al. 2008). As a result, implementing a passive radiative cooling approach, could be an effective way to establish energy-efficient buildings. Based on the cooling process operation model, building integrated radiative cooling systems can be classified into three typical categories, which are discussed below.

Air-based cooling system

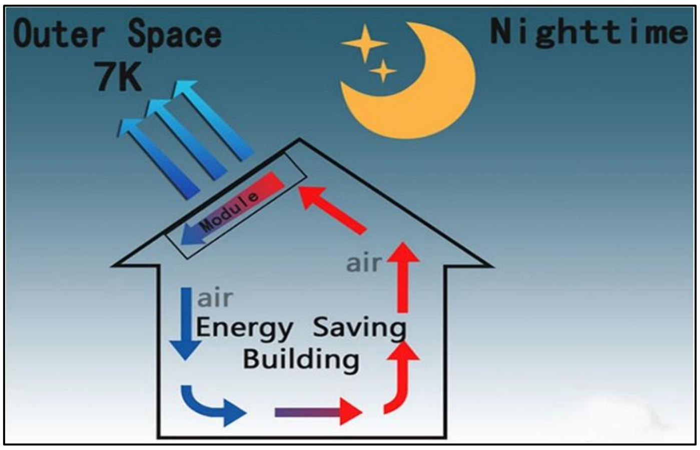

Fig. 1: Schematic of air-based radiative cooling system (Zhao et al. 2019)

Fig.1 illustrates the air-based cooling system, where air is utilized as the medium for heat exchange. The air is directly heated by the indoor environment and subsequently cooled by the radiator. In cases where natural buoyancy is used to circulate the air, the heat exchange between the air and radiator is minimal, resulting in a negligible reduction in air temperature. On the other hand, if mechanical fans are employed to force air circulation and increase the net cooling power of the system, additional electricity will be required for fan operation. Despite this, the air-based cooling system has several advantages, including a friendly structure, operation mode, and initial cost, making it a suitable option for practical applications.

Water-based cooling system

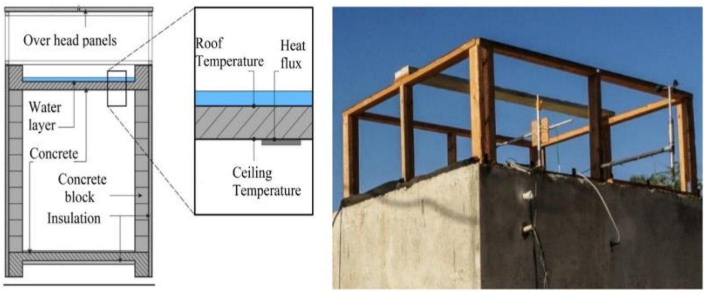

Fig.2: Schematic and actual photo of roof pond (Pearlmutter et al. 2017)

In the water-based cooling system, water is utilized as the medium for heat transfer, resulting in a significant increase in the net radiative cooling power of the system. Additionally, the water-based cooling system can be easily controlled and operated due to the higher heat capacity of water compared to air-based systems. Previous studies have identified two operating modes for the water-based cooling system:

open and closed systems. The roof pond, as shown in Fig. 2, is an example of the open system, while the flat-plate radiative system, depicted in Fig. 3, is representative of closed systems.

Hybrid system

The single-unit air- and water-based cooling systems discussed earlier are not as energy-efficient as hybrid systems that combine nocturnal radiative cooling with other energy-harvesting processes. Several hybrid systems have been developed and investigated, including radiative and evaporative cooling (RC-EC), radiative cooling and heat pump (RC-HP), and radiative cooling and solar energy utilization (RC-SE). The RC-SE hybrid system, particularly the spectral selective-based RC-SE system, has gained significant attention in recent years.

Photovoltaic cooling

The physical properties of solar cells limit the photovoltaic (PV) conversion efficiency, resulting in a maximum efficiency of approximately 33.7% for a single-gap p–n junction solar cell, as analysed by Shockley and Queisser (1961). As a result, only a portion of the absorbed solar energy can be converted into electricity, with the remaining energy being dissipated as heat, which can increase the operating temperature of the solar cells. However, high temperatures can decrease the PV efficiency, with a 1 K temperature increase reducing the relative efficiency by approximately 0.4–0.5% for a crystalline silicon solar cell. Therefore, using radiative cooling methods is a suitable approach to passively cool solar cells.

Cooling of condensers

Water-cooled thermal power plants are currently the primary option due to their high thermal efficiency, with cooling towers and ponds typically used to remove waste heat. In the United States, over 99% of thermal power plants use water-cooling methods, using up 41% of freshwater draw with 3% lost to the air, which poses a significant challenge in areas with water scarcity and frequent droughts (M. T. H. v.Vliet et al. 2016). As electrification is projected to rapidly grow in regions such as northern Africa, the Middle East, and India, water scarcity is a serious issue. Passive and enhanced cooling technologies, such as radiative sky cooling, have potential to reduce water consumption and outperform air-cooled systems in terms of efficiency.

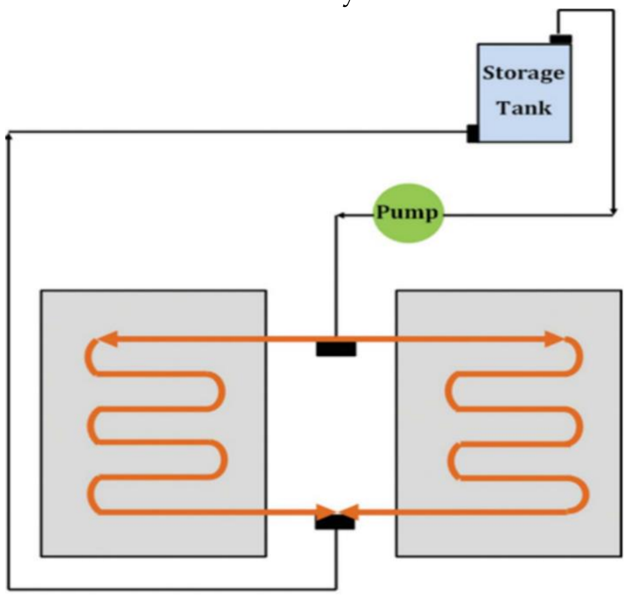

Fig. 3 Schematic of flat-plate radiative cooling system (Hosseinzadeh et al., 2012)

Dew water harvesting

When the temperature of a surface is lower than the local dew point temperature, dew forms on it. Harvesting this dew can have a significant impact on water supply in regions where traditional sources of water are limited, such as arid and semi-arid areas. The atmosphere is a vast and renewable reservoir of water, containing 12,900 cubic kilometres of water. Dew water is usually safe for consumption, particularly in rural and isolated areas like islands. There are three main methods of harvesting water from air: adsorption technology that employs adsorbent, surface cooling, and radiative sky cooling (Tu et al. 2017). Efforts have been made to analyze weather conditions, develop radiative cooling surface materials, and study operating conditions that impact the rate of water production to design effective dew collectors.

Conclusion

RSC offers enormous potential due to the significant temperature differential between the planet and deep space. Maximum reflectivity for materials suitable for the RSC should be found in the 0.25–2.5 m short wave band, while the potential material's emissivity should be close to unity in the atmospheric window and zero in the remaining wavelength range.

Due to their maximum reflectivity in the short-wave band and close to unity emissivity within the atmospheric window, metamaterials with nanophotonic structures are appropriate for continuous operation. Recently, significant progress has been made in practical applications that vary from buildings to personal thermal fabrics, deep cooling, and dew water harvesting. A sustainable passive method with minimal costs and no environmental impacts, radiative sky cooling offers a significant potential for reducing energy use, ease environmental worries, and aid in the fight against global warming.

References

Farooq, A. S., Zhang, P., Gao, Y., & Gulfam, R. (2021). Emerging radiative materials and prospective applications of radiative sky cooling-A review. *Renewable and Sustainable Energy Reviews*, *144*, 110910.

Gentle, A. R., & Smith, G. B. (2010). Radiative heat pumping from the earth using surface phonon resonant nanoparticles. Nano letters, 10(2), 373-379.

Gómez-Bombarelli, R., Aguilera-Iparraguirre, J., Hirzel, T. D., Duvenaud, D., Maclaurin, D., Blood-Forsythe, M. A., ... &Aspuru-Guzik, A. (2016). Design of efficient molecular organic light-emitting diodes by a high-throughput virtual screening and experimental approach. Nature materials, 15(10), 1120-1127.

Hosseinzadeh E, Taherian H. An experimental and analytical study of a radiative cooling system with unglazed flat plate collectors. Int J Green Energy 2012;9:766–79.

Huang, Z., & Ruan, X. (2017). Nanoparticle embedded double-layer coating for daytime radiative cooling. International journal of heat and mass transfer, 104, 890-896.

Jeong, S. Y., Tso, C. Y., Ha, J., Wong, Y. M., Chao, C. Y., Huang, B., & Qiu, H. (2020). Field investigation of a photonic multi-layered TiO2 passive radiative cooler in sub-tropical climate. Renewable Energy, 146, 44-55.

M. T. H. v. Vliet, D. Wiberg, S. Leduc, and K. Riahi, "Power-generation system vulnerability and adaptation to changes in climate and water resources," Nat. Clim. Change 6, 375–380 (2016).

Mandal, J., Fu, Y., Overvig, A. C., Jia, M., Sun, K., Shi, N. N., ... & Yang, Y. (2018). Hierarchically porous polymer coatings for highly efficient passive daytime radiative cooling. Science, 362(6412), 315-319.

Omer AM. Energy, environment and sustainable development. Renew Sustain Energy Rev 2008; 12: 2265–300.

Pearlmutter D, Berliner P. Experiments with a 'psychrometric' roof pond system for passive cooling in hot-arid regions. Energy Build 2017; 144: 295–302.

Shi, N. N., Tsai, C. C., Carter, M. J., Mandal, J., Overvig, A. C., Sfeir, M. Y., ... & Yu, N. (2018). Nanostructured fibers as a versatile photonic platform: radiative cooling and waveguiding through transverse Anderson localization. Light: Science & Applications, 7(1), 37.

Shockley W, Queisser HJ. Detailed balance limit of eciency of p-n junction solar cells. J Appl Phys 1961; 32: 510–9.

Suryawanshi, C. N., & Lin, C. T. (2009). Radiative cooling: lattice quantization and surface emissivity in thin coatings. ACS applied materials & interfaces, 1(6), 1334-1338.

Torgerson, E., & Hellhake, J. (2020). Polymer solar filter for enabling direct daytime radiative cooling. Solar Energy Materials and Solar Cells, 206, 110319.

Y. D. Tu, R. Z. Wang, T. S. Ge, and X. Zheng, "Comfortable, high-efficiency heat pump with desiccant-coated, water-sorbing heat exchangers," Sci. Rep. 7, 40437 (2017).

Zhao B, Hu M, Ao X, Pei G. Conceptual development of a building-integrated photovoltaic–radiative cooling system and preliminary performance analysis in Eastern China. Appl Energy 2017; 205: 626–34.

Zhao B, Hu M, Ao X, Chen N, Pei G. Radiative cooling: A review of fundamentals, materials, applications and prospects. Appl Energy 2019;236: 489-513.

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