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Nano Cool Paint as a Passive Cooling Strategy for Net-Zero Energy Buildings (NZEBs)

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Abstract. Energy consumption related to Air Conditioning systems in buildings has been rising rapidly due to increasing demand, climate change and the constant increase in temperature. An approach to address and minimize the consumption and its consequences is through the implementation of Net-Zero Energy Buildings (NZEBs). One technique to be used in a NZEB is radiative passive cooling and it has shown potential in overcoming such a challenge by aiding in thermal regulation which reduces energy consumption. The ability to formulate a radiative passive cooling coating with the help of nanotechnology results in a Nano Cool Paint (NCP) that can scatter incoming radiation and emit thermal radiation to the atmosphere. This work reviews the incorporation of nano-enhanced radiative passive cooling in exterior paint coatings on building facades and roofs based on available literature.

Introduction

In the recent years, studies have shown that buildings account for up to 40% of the global energy consumption [1] while relying on conventional energy sources that trigger global warming and causes overwhelming peak load demands in electricity. With the rise of population growth, urbanization and global temperatures, the cooling demand is expected to triple by 2050 if left unchecked [2]. This increasing demand required researchers to focus on energy reduction solutions rather than more efficient cooling units which has led to the implementation of Net-Zero Energy Buildings (NZEBs) due to its conceptual framework for balancing the energy being consumed and generated in a building [3]. Achieving NZEBs in regions with high demand can aggressively help in the reduction of energy consumption [4]. NZEBs concept revolves around two main designs integrated into the building, the active and passive designs. The active design corresponds to the ability of the building to provide as much power as it consumes while the passive design is the incorporation to building's envelope and structure to passively thermally regulate the building [5].

In order to implement it, passive cooling strategies – among other energy reduction strategies – are incorporated to reduce the cooling load especially in harsh arid climates. Passive cooling strategies can help in achieving high-efficiency thermal regulation with the need of zero energy

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[6]. An example of a passive cooling technique is radiative cooling (PRC) such as reflective coatings. A simple exterior reflective coating consists of an acrylic emulsion binder, fillers and functional color pigments [7]. Recent studies have shown that incorporating nanotechnology to formulate the exterior coating can help in improving the properties that enhance radiative cooling which leads to the development of Nano Cool Paint (NCP) [8], [9]. NCP's enhanced properties are solar reflectance, thermal emissivity, UV resistance and durability [10], [11], [12]. Solar reflectance maximization is the main property that allowed painted surfaces to achieve sub-ambient temperatures under direct sunlight [13]. By carefully selecting the type of nanoparticles and binder, a reflective, durable exterior paint can be developed for building in hot weather conditions. Different nanomaterials and binders have been shown to give various results where some advanced thermo-optical properties while compromising mechanical properties. The goal to implement such a technique in NZEB leads to the need to investigate the development of NCPs with a high reliability factor.

Background and Mechanism

Nano Cool Paint (NCP) is a technique of radiative cooling applied on the exterior wall of a building that helps reflect incoming solar radiation and emit thermal infrared radiation to the atmosphere within the atmospheric transparency window (8 μm to 13 μm)[14]. To increase its effectiveness, it is formulated to have high solar reflectance and high emissivity. Solar reflectance refers to the percentage of sunlight radiation that is being reflected by the surface while thermal emissivity is a percentage of the capacity of thermal irradiation into the atmosphere [15]. The role of these two properties can help in maintaining the exterior surface temperature from gaining heat. Therefore, the heat flux going into the building is reduced and thermal regulation is accomplished with the need of zero energy [16]. Fig. 1 illustrates the mechanism of NCP under direct sunlight.

The incorporation of nanomaterials has helped to push solar reflectance and emissivity beyond what conventional coatings have achieved. Studies have shown that NCP has the potential to reflect visible light and near-infrared (NIR) wavelengths that can reduce the urban heat island phenomenon [17]. This can lead to a coating capable of sub-ambient temperature cooling under direct sunlight that contributes to the energy reduction of the building [18].

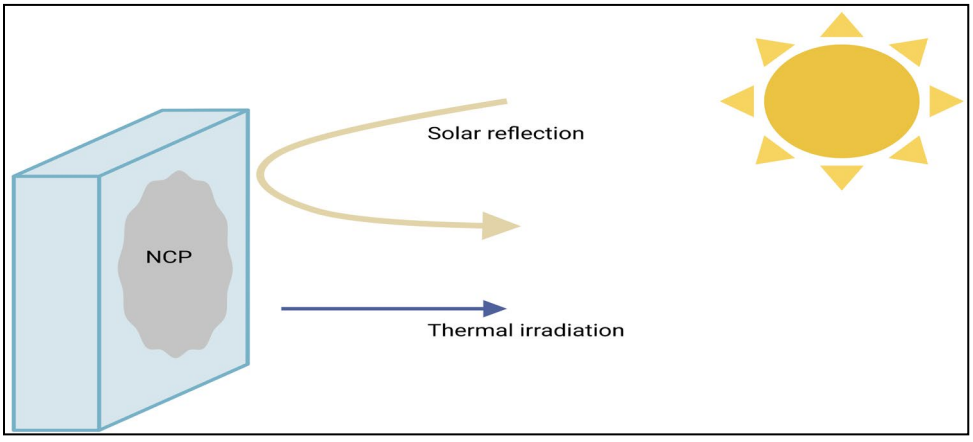


Fig. 1: Mechanism of Nano Cool Paint (NCP) under direct sunlight.

Materials and Methods

Just like any other nano fluid, Nano Cool Paint (NCP) consists of two primary materials which are a base fluid and nanomaterials. The base fluid is usually a binder or a paint emulsion where nanoparticles of any type can be dispersed in before application. In order to achieve optimum results, material selection is done based on the characteristics intended. The aim is to fabricate a

paint that can scatter light due to its high reflectance and emit thermal irradiation. Moreover, the developed paint should not lose its durability and have reliable mechanical characteristics.

Nanomaterials. In the field of radiative coating, various nanoparticles have been studied and tested based on different criteria and climate conditions. Studies have shown that the developed NCPs can lead to a highly reflective surface which can also achieve sub-ambient temperatures under direct sunlight [19]. One of the most popular nanomaterials in NCP is metal oxides [20]. For instance, high-refractive-index metal oxides like titanium dioxide (TiO_2) have been used in the paint formulations and can provide strong scattering, but its moderate bandgap (~3.3 eV) leads to some UV absorption and potential photocatalytic degradation of organic binders [21]. TiO_2 is inexpensive and non-toxic, making it abundant in white paint. One of the downsides of nano-TiO_2 is that it can be photo catalytic which makes it need to be surface treated to minimize chemical reactivity [22]. Another common metal oxide is zinc oxide (ZnO). Although studies have shown that ZnO-based NCP have better mechanical properties and durability, its light scattering performance was not as good as TiO_2 which have a higher reflectance enhancement of up to 50% compared to 28% for ZnO [20], [23]. Researchers have also explored metal oxides with a higher bandgap such as aluminum oxide Al_2O_3 and zirconium oxide ZrO_2. A higher bandgap can result in better light scattering and reduce the solar absorption which can lead to the sub-ambient temperature reduction [24], [25]. In addition to the higher reflectance percentages, Al_2O_3 and ZrO_2 showed an enhancement to the mechanical properties in comparison with other NPs. Al_2O_3 addition can lead to an anti-corrosion and hydrophobic surface which can be useful in some harsh applications [26], [27]. Similarly, ZrO_2 can enhance the mechanical properties of the NCP, thermal stability, and anti-corrosion ability [28], [29].

Another category of nanomaterials used in NCP is metal sulfates. Metal sulfates such as barium sulfate ($BaSO_4$) and calcium carbonate ($CaCO_3$) are being used in commercial paint emulsions due to their ability to act a pigment in addition to their high reflectance performance of up to ~98% [19]. Lastly, silicon-based nanoparticles (SiO_2) are known for their broadband optical scattering, strong thermal emission, and improved coating stability against weathering [30], [31]. Silicon-coated oxides and hollow spheres nanoparticles have also been investigated and found that it can lead to enhanced dispersion and thermo-optical performance [32]. In addition to the low solar absorption, hollow spheres can act as thermal insulators due to the air core.

NCP Formulation. The development of NCPs follows a selection criterion based on the type of binder (base fluid) and nanoparticles (fillers) to be dispersed for enhancement. The most common type of paint to be used on exterior facades is water-based emulsions due to its physical properties [33]. Other binder options can range from expensive silicon resin to organic binders [21], [34]. Although the base fluid is important to show durability and weather resistance, NCPs light scattering characteristics are gained from the addition of the NPs. The material selection of both is based on the overall intended characteristics. The selection of the type of binder is crucially connected to the type of NPs chosen to ensure their compatibility with the intended application. The selected materials will define and conclude other main criteria to consider in formulation such as the particle volume concentration (PVC) and coating thickness. In addition, the dispersion of the NPs is highly dependent on the type of binder used as concluded by Qazi et al. [35] where different binders showed different agglomeration and clustering results in a SEM test. Well dispersed NPs ensures that a coating will have uniform optical and mechanical properties that can help in minimizing degradation in performance and inaccurate results in testing. In addition to optical performance, binder selection plays an important role in determining the durability of NCP under harsh environmental conditions. Water-based exterior coatings are known for their hydrophobic finish but can get affected by the prolonged UV exposure [36]. Therefore, researchers such as Song et al. used a surface modifier perfluorooctyl trichlorosilane (PFOTS) as their binder which aided in overcoming the drawback of polymers' reactivity to UV light [37]. Silicon-based

binders can also provide improved UV-resistance and weather stability which can significantly enhance the long-term durability of NCP [38].

Discussion

The key properties that NCP acquire are related to its optical and thermal performance. High solar reflectance and high thermal emissivity are crucial to maximizing the coating's performance. Light-colored commercial exterior paints can have a solar reflectance of up to 80% [39]. Nano-enhanced coating has shown a great increase in solar reflectance in literature. For instance, when barium sulfate was added to a binder at a high concentration, solar reflectance of up to 97.6% and IR emissivity above 0.95 was achieved [40]. Different NPs have shown different results in enhancing optical and thermal performance. Another example is hollow Yttrium-Oxide Spheres (HYSs), which were able to enhance the reflectance and emissivity to reach superior cooling [41]. Hollow silicon-based spheres resulted in stronger reflectance in comparison with solid spheres which resulted in a temperature drop of 5.26 ˚C [42].

Low thermal conductivity can make NCPs induce a higher thermal insulation from the external heat [43]. Incorporating nanomaterials with low thermal conductivity has shown an increase in thermal performance. For instance, silica aerogel's significant low thermal conductivity (<0.05 W/mK) can outperform conventional insulators used in a building envelope [44].

Mechanical properties remain as important as the other properties of any exterior coating. With the focus being on the thermal and optical advancement of NCP, the neglect of focus on the adhesion and durability of the coating has led to NCPs that may not withstand harsh environmental conditions [45]. The addition of nanomaterials to a paint emulsion can negatively affect its adhesion and durability if not done at the appropriate ratio. A calcium carbonate-based NCP's adhesion strength can be maximized with the addition of ZnO [46].

To evaluate the performance of NCP in NZEBs, its passive cooling characteristics are taken into consideration. Solar reflectance and thermal emissivity that will contribute to exterior surface temperature reduction can thermally regulate the interior of the building. For instance, in Argentina, a reduction of 18˚C on the exterior surface of a roof coated with NCP resulted in 5˚C reduction to its internal side which corresponded to 3˚C reduction in the indoor ambient temperature [47].

Application

Field experiments and implementation of NCP have shown that lower indoor temperatures, sub-ambient cooling and reduced power demand can be achieved due to its enhancement of solar reflectance and thermal emittance into the atmosphere resulting in a passive cooling approach that can be incorporated into NZEBs [24], [48], [49]. Although lab scale studies are available, especially in recent years, real-life applications are limited in hot arid climate conditions.

A simulation study of a building in Al Mizhar, UAE, was conducted using IES VE software and a reduction of energy of 47% was concluded [50]. Another simulation of different regions of the US showed that hot climate conditions resulted in more electricity savings of up to 9.31 kWh/m^2 [51]. A double-layer coatings composed of densely packed TiO_2 and SiO_2 or SiC nanoparticles, can cool an Al foil up to 8 °C at daytime and 5 °C at nighttime in Shanghai, China. It also helps to cool the black surface for more than 30°C at daytime [52]. An experimental performance evaluation of a porous polymer radiative coating (PPRC) reflectance was found to be 93% in the visible wave band (0.38–0.78 μm) which shows that optical capability of the doped nano/micro-porous structures where a drop of temperature and cooling load of up to 7.6℃ and 85.9 W/m^2 was achieved at noon and up to 12.8 °C and 120.9 W/m^2 at night under moderate relative humidity and a clear sky as shown in Fig. 2 [53]. Although the performance of this developed NCP was highly affected by Shanghai humid weather, it still shows evidence of the role

radiative cooling can contribute in NZEBs. A similar study consists of TiO_2 and SiO_2 as NPs was found to result in a solar reflectance of 92.68 % and surface temperature reduction of 9.5 ℃ [11].

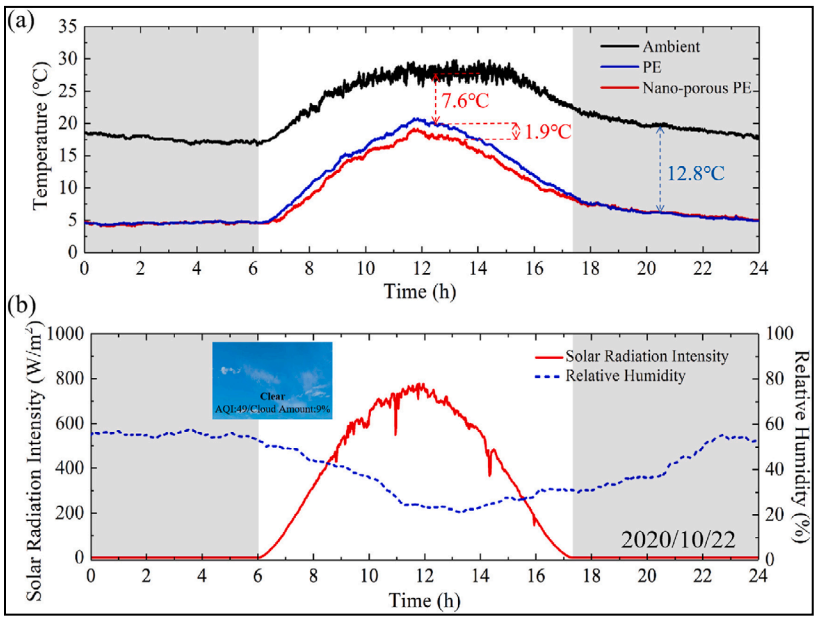


Fig. 2: (a) The temperature variation of the PPRC with PE film (blue) or nano-porous PE film (red) (b) The weather conditions during the test [53].

Different types of nanomaterials can result in different cooling results. Nanoporous Mg-doped SiO_2 nanoparticles were used to develop a coating that has resulted in tunable infrared emissivity and 86.2% solar reflectance. The coating exhibited high radiative cooling performance and a temperature reduction of 17.8 °C lower than the control [54]. A solar reflectance of 97.6% was achieved by the formulation of an NCP that consists of properly designed $BaSO_4$, $CaCO_3$ and SiO_2. The results showed a surface temperature of 5.5 C lower than commercial white paints and a theoretical RC power of 119.3 W/m^2 and 94.3 W/m^2 at nighttime and daytime, respectively [55]. Moreover, nanomaterials made of broken glass bubbles (BGB) were incorporated in nanoporous polyethylene (NanoPE) film resulted in solar reflectance of 97.3 % and 8.5 ℃ temperature reduction at noon and up to a 14.1 °C reduction at night. Compared with the glass bubbles (GB) and broken glass bubbles (BGB), the NanoPE film can boost the cooling performance of the coating during the whole day significantly as shown in Fig. 3 [56].

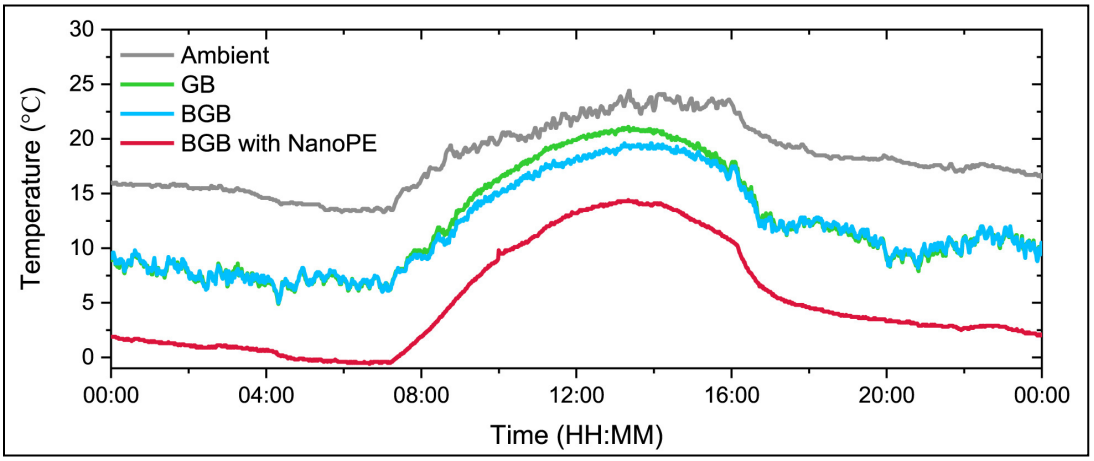


Fig 3: Temperature of ambient air/GB/BGB/BGB with NanoPE over a 24-h period in a field test in Hong Kong [56].

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Limitations and Challenges

Aesthetic. High reflectance values have mostly been achieved with ultra-white coatings using white fillers which can correspond to more light scattering [13], [57]. In the buildings sector, architects and individuals often prefer colored exterior surfaces for aesthetic purposes. Recent research is investigating the possibility of incorporating color without compromising the properties of NCP. For instance, an optimized TiO_2 to reduce glare and brightness has led to negatively affecting the energy reduction by 7% with only a 30% difference in brightness [58]. Ultra-white NCP coatings can achieve a solar reflectance of up to 0.98 [40]; however, darker pigments can degrade such enhancements due to the increased absorption in the visible spectrum. A bilayer radiative coating technique with different pigments such as yellow, green and red was tested and a gradual decrease in solar reflectance is observed as the color darkens as shown in Table 1. A recent study found that fluorescent colored radiative cooling coatings present a scalable alternative to ultra-white coatings with maintaining a reflectance of 95%. The downside of such coatings is their high cost and degradation problems [59]. Click or tap here to enter text.

Table 1. Effect of coating color on solar reflectance of nano cool paint (NCP) coatings.

Coating color	Solar Reflectance	Ref.
Ultra-white	0.97	[40]
Yellow	0.91	[60]
Green	0.89	
Red	0.84	

Aging. Degradation of the mechanical, optical and thermal properties is a great limitation with existing NCPs. While continuous studies have found that various materials can reach high IR emissivity values in the longwave infrared spectrum [61]. However, reflectance deterioration might occur from aging. Since the coating is applied on an exterior wall, deterioration is prone to happen due to the exposure to the open atmosphere. Surface soiling due to the buildup of dust or other particles can cause the aged reflectance to decrease significantly [62]. Studies have concluded that most surfaces lose up to 25% of their initial solar reflectance index after 3 years of being applied if left unwashed [63]. To maintain long-term reliability and cooling performance in NZEBs applications, maintenance protocols should be considered. Scheduled or nature-assisted surface cleaning can help in maintaining the solar reflectance of the coating. Mesoporous silica aerogel (SA) infused coatings has shown great potential in enhancing the reflectance to the solar irradiance by up to 15% in the visible and near-infrared ranges (0.3-2.5 μm) while maintaining the surface hydrophobicity and self-cleaning characteristics which increases its durability against soiling and contaminations [61].Another factor that can lead to paint degradation is Ultraviolet (UV) radiation. Continuous exposure to UV radiation has caused a huge drop in energy savings of about 3.8 $kWhm^{-2}$ due to aging [64]. Although the addition of NPs such as ZnO has shown improved UV resistance, continuous exposure makes it a short-term solution in buildings sector [12]. Moreover, humid climate conditions can exhibit a form of degradation and yellowing in paints which makes it not applicable for tropical regions [65]. With the increase in relative humidity in tropical regions, the water vapor content in air increases and reduces the amount of heat radiated from the surface due to it being a major absorber of infrared radiation[66].For instance, radiative coolers that performed effectively in a dry region failed to achieve similar sub-ambient cooling performance in a hot humid region [49]. A study conducted in Malaysia's tropical climate has found that although the net cooling power of the paints had an inverse relationship with relative humidity, the sub-ambient cooling was achievable with coatings having a pigment PVC% at 60% and 70% for barium sulfate and calcium carbonate, respectively [19]. Moreover, surface moisture and condensation can degrade the solar reflectance by acting as a barrier between the NCP coating and the atmosphere which can be addressed by surface modification of NCP by

making it more hydrophobic [67]. Researchers have examined and proposed different strategies such as high PVC%, surface modifications and structural strategies [19], [68], [69]. For instance, dual-layer coating has aided in sub-ambient cooling in Shanghai, China's humid climate [69].

Conclusion

The increase in demand toward Net-Zero Energy Buildings (NZEBs) due to the global climate conditions and electricity demands has led to recognizing the importance of incorporating innovative passive cooling strategies to its design. Nano-enhanced materials that can be integrated into the building's envelope can aid in thermal regulation and decrease the load put on the HVAC systems. Such approaches can be passive radiative cooling such as Nano Cool Paint (NCP) which is promised to lead toward a sustainable, Net-Zero energy future due to its proven efficacy in thermal regulation. NCP's high solar reflectance and emissivity contribute to radiative cooling that can help in energy and exterior surface temperature reduction. The application of NCP does not vary a lot from the standard painting processes which makes it a simple addition to either new or existing building that does not require any sort of structural modification. Existing studies and research have focused on the optical properties of NCPs as a fresh coat/sample. However, to be integrated into a NZEB and achieve its promised purpose, the long-term performance must be investigated as well. NCP outcome can vary considerably by climate and weather conditions which can have a negative effect on its mechanical and optical properties. Humid climates were found to face limitations due to existing water vapor that can interfere with the mechanism of NCP. In addition, accumulation of dust on exterior surfaces in dessert climates can decrease the solar reflectance significantly affecting its performance. Proper maintenance can help in securing the optimal efficacy of NCPs as a part of NZEB operational life. Further investigation in the material selection and application procedures will emphasize the need for research to start focusing more on the mechanical properties' enhancement of NCPs such as self-cleaning, UV-resistance or adhesion. Succeeding to meet an enhancement in optical properties while maintaining or enhancing mechanical properties can lead to securing a long-term reliability of NCPs to be used as a part of a NZEB strategy. In addition, the ability to include a wider color range of darker colors will increase its demand in the architectural perspective.

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