Radiative cooling wrapping films with controlled hierarchical porous structures

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Research Article

Keywords: Passive radiative cooling, thermoplastic polyurethane, bimodal pore structure, solar reflectivity, long-wavelength infrared emissivity

Posted Date: September 2nd, 2022

DOI: https://doi.org/10.21203/rs.3.rs-2007976/v1

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Abstract

Current research has focused on effective solutions to mitigate global warming and the accelerating greenhouse gas emissions. Compared to most cooling methods requiring energy and resources, passive daytime radiative cooling (PDRC) technology offers excellent energy savings as it requires no energy consumption. However, existing PDRC materials encounter unprecedented problems such as complex structures, low flexibility, and performance degradation after stretching. Thus, this study reports a porous structured thermoplastic polyurethane (TPU) film with bimodal pores to produce high-efficiency PDRC with efficient solar scattering using a simple process. The TPU film exhibited an adequately high solar reflectivity of 0.93 and an emissivity of 0.90 in the atmospheric window to achieve an ambient cooling of 5.6°C at midday under a solar intensity of 800 W/m². Thus, the highly elastic and flexible TPU film was extremely suitable for application on objects with complex shapes. The radiative cooling performance of 3D-printed models covered with these TPU films demonstrated their superior indoor cooling efficiency compared to commercial white paint (8.76°C). Thus, the proposed design of high-efficiency PDRC materials is applicable in various urban infrastructural objects such as buildings and vehicles.

1. Introduction

Recently, passive radiative cooling structures are being actively studied due to their applicability during daytime.\(^1\text{–}^3\) The development of passive daytime radiative cooling (PDRC) technology can aid energy-saving systems, and it is considered an eco-friendly future technology that can be applied to various fields such as buildings, vehicles, and solar cells. In context, radiative cooling occurs when the amount of emitted radiant energy is greater than that of the absorbed radiant energy. Generally, the Earth maintains heat balance by emitting radiation as infrared rays. Therefore, cooling by radiative heat transfer can reduce the surface temperature below the external temperature without additional energy input because of the heat transfer by radiation between the Earth's surface or an emitter (~ 300 K) and cold outer space (at ~ 3 K). The PDRC can lower its temperature by emitting thermal energy into the outer space as wavelengths ranging within 8–13 µm (atmospheric window). However, when the cooling demand is high during the day, insolation (~ 1000 W/m²) is higher than that of radiative cooling (~ 100 W/m²), offsetting the effect of radiative cooling. Therefore, several studies reported an improvement in long-wavelength infrared (LWIR) emissivity and solar reflectivity in the wavelength range of 0.3–2.5 µm.

Primarily, micro/nano-size materials such as photonic structures, nanoparticle-doped materials, and metamaterials have been designed and fabricated for high radiative cooling performance.\(^4\text{–}^9\) For instance, Y. Zhai et al. proposed a scalable-manufactured PDRC by randomly inserting micrometer-sized SiO\(_2\) spheres into the matrix of polymethylpentene (TPX).\(^9\) This metamaterial exhibited strong heat dissipation with an infrared emissivity greater than 0.93. The results of an external test demonstrated a net cooling power of 93 W/m². Moreover, Raman et al. proposed a photon emission cooler with seven layers of HfO\(_2\) and SiO\(_2\) that could cool to 4.9°C below the ambient air temperature.\(^5\) Although the multilayer structure and the utilization of silver metal layers proposed in prior studies provided excellent
solar reflection, the practical application of inflexible materials on the exterior of real buildings and automobiles is still limited. Therefore, more flexible and stretchable materials should be used for indoor cooling effects.

Recently, radiative cooling materials based on polymers have been actively studied. According to a recent study, a polymer with a porous structure that induces light scattering without a separate reflective layer enables high reflectivity in the solar region. Examples include polyvinylidene fluoride (PVDF)\textsuperscript{10–12}, polydimethylsiloxane (PDMS)\textsuperscript{13}, polyethylene (PE)\textsuperscript{14–16}, polyethylene oxide (PEO)\textsuperscript{17}, and thermoplastic polyurethane (TPU)\textsuperscript{18,19}. Among them, TPU is widely used in automotive coatings and various foams, and has excellent elongation, tensile strength, and abrasion resistance. The previously proposed TPU-based cooling material consists of a composite material. A simple process and the use of inexpensive materials are important for efficient passive radiative cooling. Therefore, we propose a completely organic material using only polymers. In addition, our proposed TPU-based cooling material uses a hierarchical pore structure to provide higher optical properties. In this study, we propose a stretchable TPU cooler film for efficient radiative cooling (Fig. 1). The TPU film is flexible and exhibits high elasticity due to its elastomer properties, rendering it an ideal selection for actual applications. A bimodal pore-scale suitable for light scattering in the TPU matrix was prepared using the thermally induced phase separation (TIPS) process to achieve a high solar reflection. Bimodal pores possess a hierarchical multimodal pore size distribution of small groups and large groups. The TPU film is an excellent new material for application as exterior materials for buildings and vehicles because its reflectivity does not decrease even after stretching. The proposed TPU cooler demonstrated superior solar reflectivity (0.93), LWIR emissivity (0.90), and high porosity (78.8%). In addition, we performed outdoor tests using 3D-printed models (house, dome, and bus) to demonstrate its potential for radiative cooling application. The current research aims to verify the applicability of the TPU cooler on various structures without limitation; thus, a cooling form factor was proposed to enable its effective application. Therefore, we aim to develop a flexible and stretchable PDRC coating material to formulate a technological and economic strategy for saving energy.

2. Results And Discussion

2.1. Design of thermoplastic polyurethane for passive radiative cooling

As presented in Fig. 2a, we fabricated a structured TPU film with bimodal pores for efficient radiative cooling. The porous TPU film was prepared using the thermally induced phase separation (TIPS) method, a widely adopted preparation procedure for porous structured materials.\textsuperscript{15,16,20–22}

During the manufacturing process, deionized water was added to the TPU/dioxane solution, and upon cooling, the phase forming the dioxane crystals was separated from TPU and water; subsequently, the deionized water was crystallized, and the phase separated. During the freeze-drying process, the
sublimation of iced dioxane crystals and water formed interconnected pores; as demonstrated by the cross-sectional SEM image in Fig. 2b, bimodal pores were appropriately formed. A comparison of the structure and pore size based on the polymer content revealed that the cell pore size decreased with the increasing polymer concentration (Figure S1a). In this case, the pores were not appropriately formed for a TPU content \( \leq 3 \) wt.%. In contrast, a homogeneous solution could not be obtained in dioxane/water (9.5:0.5) if the TPU concentration exceeded 15 wt.%. In particular, these results can be attributed to the polymer content. As the polymer concentration decreased, the phase separation rate gradually reduced, and the gelation time increased; thus, there was sufficient time for the coarsening process,[23] resulting in a larger pore size. As depicted in Figure S2, the pore size is over 50 µm for a polymer content of 5 wt.%, but it decreases to less than 25 µm if the polymer content increases beyond 10 wt.%. Therefore, a polymer content of 10 wt.% yields a hierarchical structure and was thus selected as the optimal pore size.

The average pore diameter of the TPU film obtained from 10 wt.% TPU solution is depicted in Fig. 2c; the average pore diameter \( (D) \) of the TPU film was calculated using the following equation:

\[
D = \frac{\sum d_i n_i}{\sum n_i}
\]

where \( d_i \) denotes the single pore diameter, \( n_i \) represents the number of pores in the SEM micrograph from which the average pore diameter \( (D) \) can be estimated. Moreover, the size analysis and calculations revealed that the pore sizes of the TPU film were 3.0 and 22.4 µm, respectively. Therefore, the porous TPU film exhibited well-defined bimodal pores and could provide enhanced solar reflection for high radiative-cooling performance.

2.2. Optical properties of TPU with bimodal pores

The as-prepared TPU coolers provide ideal solar reflectivity and high emissivity in the atmospheric window (8–13 µm of wavelength). As observed in Fig. 3a, the porous TPU structure exhibited higher solar reflectivity compared to the non-porous TPU, attributed to the light-backscattering by the increased bimodal pore interface in the TPU matrix. To investigate an effect of a pore morphology on the light scattering, we measured the reflectivity and emissivity of TPU films for various polymer concentrations. The TPU concentration of 10 wt.% yields the highest reflectivity in the visible and short-wave infrared (SWIR) region (Figure S1b and c). As mentioned above, the TPU cooler fabricated with a TPU concentration of 10 wt.% exhibited a well-defined porous structure and bimodal appearance compared to other TPU films (Figure S2). Therefore, these results suggest that the bimodal pore morphology increases a light scattering. This phenomenon is prominently illustrated by the finite-difference time-domain (FDTD) simulation results in the 0.3–2.5 µm wavelength range and demonstrated that the TPU cooler with pore sizes of 3.0 and 22.4 µm exhibited a high scattering efficiency (Fig. 3c).[24] When the pore size is larger than 1.0 µm, sunlight can be efficiently scattered regardless of the wavelength (Figure S3). The TPU cooler with bimodal pores have average diameters of 3.0 and 22.4 µm, as shown in Fig. 2c. Therefore, the
TPU cooler having bimodal pore size distributions has a high solar reflectivity due to an optical scattering by multiple interfaces. In addition, the solar reflectivity in the wavelength range of 0.2–2.4 µm were obtained using the FDTD simulation to recognize the influence of the bimodal pore structures on their optical properties. In particular, the pore diameters of 3.0 µm, 22.4 µm, and the bimodal pores of 3.0 µm and 22.4 µm were selected to compare the optical properties. As depicted in Fig. 3b, the non-porous TPU displayed extremely low reflectivity, consistent with the measured spectral reflectivity and indicating that the TPU with pores could strongly reflect sunlight due to backscattering. Moreover, the TPU cooler with bimodal pores (d = 3.0 and 22.4 µm) displayed higher solar reflectivity than 3.0 µm and 22.4 µm with single pore size due to multiple scattering by multiple interfaces. Therefore, these simulation results appropriately explain the contribution of the bimodal diameter pores toward solar reflectivity.

The spectral emissivity in the atmospheric window of non-porous and porous TPU is illustrated in Fig. 3c, depicting high LWIR emissivity of both the TPU films caused by the vibrational absorption of the TPU. In particular, the soft and hard segments in the TPU were linked together by covalent bonds to actually form the copolymers. Here, the C-O functional group corresponding to the soft segment and the amide group (-NHCO-) corresponding to the hard segment have strong absorption in the atmospheric window region due to bending vibration. The oscillating portion in the infrared region (λ = 2.5–25 µm) included molecular oscillations that caused absorption in the electromagnetic spectrum (refer to Figure S5). Interestingly, the TPU with bimodal pores manifested a higher selective emissivity than the non-porous TPU due to the reflection in the NIR region. Specifically, the selective emitter delivered higher radiative cooling performance because the absorption of the radiant heat by an atmosphere outside the atmospheric window region is limited.\[16,25,26\] Therefore, the porous TPU can realize the ideal cooling performance in the daytime compared to the non-porous TPU. In addition, the non-directional isotropic pores have a high emissivity due to diffuse reflection regardless of the angle of incidence. As shown in Fig. 3e and f, high emissivity was maintained in various incident angle ranges (10–80°).

2.3. Passive radiative cooling efficiency and temperature profile

The radiative cooling performance of the as-prepared TPU cooler is shown in Fig. 4. For the outdoor test, the equipment was composed of polystyrene to block the absorption of sunlight and was covered with a silver reflective film to prevent the absorption of sunlight. In addition, the gap between the sample and the low-density polyethylene (LDPE) film was 30 mm, and the transparent LDPE film was designed in consideration of high transparency in the atmospheric window.\[17,27,28\] As presented in Fig. 4a, the ambient temperatures of the TPU cooler were measured using thermocouples to evaluate the radiative cooling performance of the TPU cooler, and the outdoor tests were performed in various locations. Moreover, an additional experiment was conducted in Jeju Island on May 13, 2021, a humid area in South Korea (Fig. 4c); despite the humidity, the TPU cooler produced an average cooling effect of 4.5°C compared to the ambient temperature. The theoretical cooling power of the TPU cooler is charted in Fig. 4d and e. As the cooling performance is affected by the non-radiative heat transfer, the net cooling power was calculated, assuming the non-radiative heat transfer coefficient (h_c) as 0, 3, 6, 9, and 12
The theoretical cooling power was 163.9 W/m² under a solar irradiance of 800 W/m², assuming an ambient temperature of 310 K (Fig. 4e). The results presented in Figure S8 also indicate that the porous TPU cooler provides significantly more cooling during the day than the non-porous TPU. This is due to the bimodal porous structure of the TPU cooler, which improves the radiative cooling performance by increasing the reflectivity due to the increase of multiple scattering. Additionally, in Daejeon, South Korea on May 13, 2021, the TPU cooler averaged 5.6°C cooling compared to ambient temperature for 4 hours and provided an average of 1.2°C cooling at night on May 18, 2021 (Figure S7).

2.4. Mechanical properties of TPU cooler

In previous studies, radiative cooling was achieved using a photonic structure with dielectric particle and layer structures,[7, 12, 16, 29, 30] nonetheless, rigid materials can limit their application in real-world buildings and transportation equipment. As the TPU is a representative elastomeric polymer providing high flexibility and elasticity, it is advantageous for application in buildings and transportation equipment. In addition, several prior studies have reported thermal coolers with adequate flexibility for attachment to buildings.[25, 31, 32] Therefore, high cooling performance should be achieved for practical applications even at a bent or stretched state. Accordingly, we performed a stretchability test of the as-prepared TPU film to evaluate the variation of optical properties in the stretched state. A 1-mm-thick TPU cooler was stretched from 0 to 120% to measure the reflectivity based on tensile strain (Figure S4 and Table S1). As depicted in Fig. 5, the reflectivity of the TPU cooler slightly decreased due to the deformation of the pores under the increasing tensile strain; regardless, it still delivered a high solar reflectivity of 88.89%. Compared to the average emissivity in the unstretched state, the emissivity slightly decreased by approximately 4%. Therefore, these results signified that the radiative cooling performance of the TPU cooler can be maintained when applied to objects with various shapes.

2.5. 3D model of TPU cooler and Outdoor test

We experimented with 3D-printed buildings and vehicles to approximate the real situation. As depicted in Fig. 6, various 3D models, such as houses, domes, and buses were produced. In addition, three identical specimens were prepared for the test conditions of commercial filament (model-bare), coated commercial white paint (model-paint), and coated TPU cooler (model-TPU). In this case, the filament was considered grey to represent the typical cement color. An external temperature test was conducted on September 15, 2021, in Daejeon, under direct sunlight of 912 Wm⁻² (Fig. 6b). Consequently, the TPU cooler coating achieved excellent daytime radiative cooling under high solar heat. For accurate measurement, a K-type thermocouple was used to measure the internal temperature of a 3D model, and the surface temperature was measured using a thermal imaging camera(Figure S6). On average, the house-TPU was cooled by 36.7 and 8.76°C than the house-bare and house-paint, respectively. In addition, the dome-TPU was cooled by 30.47 and 5.87°C on average than the dome-bare and dome-paint, respectively. Lastly, the bus-TPU was cooled by an average of 22.2 and 1.89°C in comparison to the bus-bare and bus-paint, respectively. These results implied that the TPU cooler produced the highest solar reflectivity when compared to the
reflectivity in the UV and visible wavelength regions of the filament, paint, and TPU coolers. Among the three models, the house reflected the highest cooling power because of the larger ratio of the roof cooling area to the total area of the object (Fig. 6c, S10 and Table S3). Furthermore, this reflected the cooling form factor and excellent radiative cooling potential of the coated TPU material. Although several meteorological parameters of radiative cooling are unavoidable, the TPU cooler can be coated on various models, as it delivered high cooling performance with little reduction in reflectivity even when stretched. The cooling form factor calculations suggested promising radiative cooling materials and designs as they can enhance the energy-saving potential of buildings at an early design stage.

3. Conclusion

In this study, we developed a stretchable TPU that can be coated on city buildings using a simple process for PDRC applications. The bimodal pore structure of the TPU exhibited high reflectivity at solar wavelengths due to the backscattering of sunlight and high solar reflection even after stretching up to 120% tensile strain. In addition, the molecular vibrations occurred because of chemical covalent bonding and produced a selective high emissivity in the atmospheric window. Surprisingly, the TPU-based PDRC coating reflected a cooling effect that is 5.6°C lower than the ambient temperature; it displayed the excellent cooling effect even in humid areas. Moreover, we 3D-printed various urban structures to apply the coating of the TPU cooler, which demonstrated a cooling effect of 8.76°C lower than the actual exterior cement color and commercial white paint. Furthermore, the durability tests proved its potential for practical applications in buildings.

4. Experimental Section

Materials

The TPU (Mₙ = 155,500 g/mol) was procured from Sambu Fine Chemical (TPU, T95-A), and 1,4-dioxane (99.0%; Sigma-Aldrich Co. Ltd.) was used as the solvent. Zikasorb-R (ZIKO) was used as the UV absorber, and Songnox® 2450 (Songwon) was used as the antioxidant. In addition, distilled deionized (DDI) water was used in all experiments.

Fabrication of TPU coolers: The TPU pellets blended with the UV absorber (0.022 g), antioxidant (0.022 g), 1,4-dioxane (61.8 g), and water (3.25 g) were introduced into a 100 mL vial. In particular, the TPU solutions were prepared in a water bath at 60 °C by mixing with a magnetic stirrer. Thereafter, a homogeneous TPU solution was cast onto a glass dish and covered with a lid. The TPU solution with a concentration of 10 wt.% was quenched at a temperature of −24 °C for 12 h during the TIPS process. Moreover, a 9.5:0.5 dioxane/water solvent system was used for the liquid–liquid phase separation of the TPU in the solution. Ultimately, the glass dish containing the TPU gel was completely phase separated and transferred to a freeze-drying vessel (LYFC, Operon advantech) at −120 °C for 72 h at 760 torr. The white TPU coolers can be fabricated in various shapes and sizes, and the optimal sample thickness was selected based on its optical properties (e.g., solar reflectivity and LWIR emissivity).
Fabrication of 3D printing model TPU coolers

PLA filaments with a diameter of 1.75 mm were procured from a commercial 3D-printing filament manufacturer. The test specimens were printed on a Stealth 450 3D printer (ROKIT company) using a grey PLA filament. Specifically, the printing and bed temperatures during the process were maintained at 210 and 80 °C, respectively. Moreover, three identical specimens were prepared for the test conditions of commercial filament (bare), commercial white paint, and TPU cooler. Commercial paint was sprayed with a uniform thickness on the manufactured 3D model, and the TPU cooler was coated by stretching with a commercial adhesive.

Characterization of optical properties

The reflectivity and transmissivity spectra were measured in the 0.3–2.5 µm range using a spectrophotometer (Cary 5000, Agilent Technologies) with an integrating sphere (DRA-2500, Agilent Technologies). Additionally, a Fourier-transform infrared spectrometer (Vertex 80v, Bruker) equipped with a gold-integrating sphere (DTGS, PIKE Technologies) was used to measure the IR absorbance in the 2.5–25 µm range. The angular reflectivity of the TPU cooler in the atmospheric window region (8–13 µm) was measured at polar angles ranging from 10–70°. Overall, the emissivity measurements were defined according to Kirchhoff’s radiation law.

Calculation of cooling power

The net cooling power of the radiative cooler was calculated using MATLAB. The energy balance can be expressed as

\[
P_{\text{net}}(T) = P_{\text{rad}}(T) - P_{\text{Sun}} - P_{\text{atm}}(T_{\text{ambient}}) - P_{\text{non, rad}}
\]

where \(P_{\text{rad}}(T)\) denotes the thermal radiation power at the temperature \(T\) of the cooler surface and \(P_{\text{Sun}}\) denotes the solar power absorbed by the cooler. \(P_{\text{atm}}(T_{\text{ambient}})\) represents the absorbed atmosphere thermal radiation power at ambient temperature \(T_{\text{ambient}}\), and \(P_{\text{non, rad}}\) represents the non-radiative power by heat exchange between the cooler and surrounding environment. These terms can be defined as the following equations:

\[
P_{\text{rad}}(T) = A \int d\Omega \cos \theta \int_0^\infty d\lambda I_{BB}(T, \lambda) \epsilon(\lambda, \theta)
\]

\[
P_{\text{Sun}} = A \int_0^\infty d\lambda \epsilon(\lambda, \theta) I_{AM1.5}(\lambda)
\]
\[
P_{atm}(T_{amb}) = A \int d\Omega \cos \theta \int_0^\infty d\lambda I_B(T_{amb}, \lambda) e(\lambda, \theta) e_{atm}(\lambda, \theta)
\]

\[
P_{non, rad} = Ah_c(T_{amb} - T_{sam})
\]

where \( \int d\theta = 2\pi \int_0^{\pi/2} \) represents the hemispheric angular integral. Furthermore, the spectral radiance of a blackbody at the absolute temperature \( T \) can be expressed using Planck's equation:

\[
I_{BB} = \left(\frac{2hc^2}{\lambda^5}\right)/\left[e^{hc/\left(\lambda\kappa_BT\right)} - 1\right]
\]

where \( h \) denotes the Planck's constant, \( c \) represents the speed of the light, and \( \kappa_B \) denotes the Boltzmann's constant. \( e_{atm}(\lambda, \theta) = 1 - t(\lambda)^{1/\cos \theta} \) indicates the atmosphere emissivity, where \( t(\lambda) \) represents the atmospheric transmittance in the zenith direction. In Eq. (6), \( h_c = h_{\text{cond}} + h_{\text{conv}} \) expresses a non-radiative heat transfer coefficient by conductive and convective heating. The theoretical cooling power was evaluated, assuming a steady ambient environment, including various \( h_c \) values of 0, 3, 6, 9, and 12 W/m²K, and the reduction of cooling power by LDPE film. The absorption of solar irradiation and thermal radiation using the LDPE film were considered because the coolers were placed under the LDPE film.

**Finite-difference time-domain (FDTD) simulations**

The scattering efficiency and solar reflectivity of the embedded pores of the porous TPU were performed using FDTD Solutions (V8.26.2865, ANSYS Lumerical software). For the simulation of scattering efficiency, a polymer with pores ranging within 3.0–22.4 µm was used as the scattering medium. The refractive index of the pores was 1, and the refractive index of the TPU was derived from a previous publication.[33] In addition, a TFSF wave source was used for scattering efficiency simulation, and a plane wave source of normal incidence was used for solar reflectivity measurement. Moreover, the unit cell for measuring solar reflectivity was set to a uniform thickness of 300 µm and tailored to create randomly distributed pores of a set diameter. The reflectivity was monitored by placing the frequency domain field and the power monitor on the base plane wave source of the unit cell.

**Measurement of outdoor radiative cooling performance**
We tested the real-time temperature and cooling power in two cities in South Korea (longitude 127.38°, latitude 36.35° for Daejeon and longitude 126.41°, latitude 33.26° for Jeju Island). The size of each prepared sample was 3.0 cm × 3.0 cm, and the sample was composed of polystyrene foam (400 × 500 × 600 mm³) to reduce heat conduction from the ground; the outer wall was covered with a silver reflective film. Moreover, a 150-µm-thick low-density polyethylene (LDPE) film was used to effectively suppress convection and conduction. The distance between the sample and the LDPE film was 30 mm. Subsequently, a multichannel temperature data logger (PCE instrument UK Ltd., PCE-T 1200) and a K-type thermocouple were inserted into each sample to measure the temperature. The insolation was measured using a thermopile pyrometer (Apogee Instruments, SP-510 solar system), and the illuminance data were acquired at intervals of 10 s in a microcache AT-100 data logger. All instruments and solar systems were placed horizontally.

**Microscopic imaging and porosity**

The analysis of the porous structure in the TPU was performed using SEM (Tescan Mira 3 LMU FEG, Tescan) at an accelerating voltage of 10 kV. The cross-sections of the samples were prepared using a sharp knife under liquid nitrogen (LN₂) and coated with Pt for 120 s at 10 mA using a sputter-coater (Q150T ES, Quorum). The pore-size analysis was performed using the Image-J software, and the total porosity was examined using a mercury intrusion porosimeter (MicroActive AutoPore V 9600, Micrometerics).

**Declarations**

**Author contribution**

Choyeon Park: conceptualization, formal analysis, FDTD simulation, writing - original draft & editing; Chanil Park: methodology, formal analysis, investigation, writing - original draft; Sungmin Park: formal analysis, FDTD simulation, energy consumption analysis, writing – editing; Jae-Hak Choi, Yong Seok Kim, and Youngjae Yoo: project administration, writing-review & editing, supervision. All authors reviewed the manuscript.

**Funding**

This work was supported by the Korea Research Institute of Chemical Technology (KRICT) core project (SS2121-20) and the Industrial Strategic Technology Development Program (20011165) funded by the Ministry of Trade, Industry & Energy (MOTIE, Korea). This study was also supported by the Chung-Ang University Research Scholarship Grants in 2022.

**Conflict of interest**

The authors declare no competing interests.
References


Figures

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**Figure 1**

(a) Schematic of passive radiative cooling using TPU cooler. (b) Reflectivity and (c) emissivity of ideal selective thermal emitter.
Figure 2

(a) Schematic illustration of the thermally induced phase separation (TIPS) process for preparation of TPU cooler, (b) cross-sectional SEM image of the TPU cooler (x1000), (c) pore size distribution of the TPU cooler; pore sizes of the TPU are 3.0 μm and 22.4 μm, respectively.
Figure 3

(a) Reflectivity of the porous TPU coolers and non-porous TPU in the wavelength range of 0.4-25 μm (thickness of 2 mm). (b) FDTD simulated spectral reflectivity of porous TPU cooler with pore diameters of 3.0 μm and 22.4 μm and a bimodal porous structure and (c) scattering efficiency of porous TPUs with various pore diameters (3.0, 22.4 μm). (d) Emissivity of the porous TPU coolers and non-porous TPU in the wavelength range of 0.4-25 μm (thickness of 2 mm). (e) Angular emissivity of the porous TPU coolers with various incident angles in wavelength range of 8–13 μm. (f) Emissivity spectra of the porous TPU cooler at various polar angles in mid- and long-wavelength infrared (LWIR) regions.

Figure 4

(a) Schematic illustration and photographic image of experimental setup. (b) Outdoor experimental results for porous TPU cooler and ambient in various locations and weathers in Daejeon city and (c) relatively humid Jeju island (d) Theoretical cooling power of porous TPU cooler according to ambient temperature. Calculation uses non-radiative heat transfer coefficient ($h_c$) of 6 W/m$^2$K. (e) Theoretical cooling power of TPU cooler at ambient temperature of 310 K. Heat transfer coefficient values ($h_c = 0, 3, 6, 9, 12$ W/m$^2$K) are used in calculations.
Figure 5

(a) Reflectivity spectra of TPU cooler for various stretching strain; 0–120 %. (b) Emissivity spectra of TPU cooler for varying stretching strains; 0–120 % in mid- and long-wavelength infrared (LWIR) region of 8–13 μm. (c) Average reflectivity in wavelength range 0.4–1.1 μm and average LWIR emissivity. (d) Optical images of TPU cooler under stretching strain of 0–120 %.
Figure 6

(a) Thermographic image of bare, white paint, and TPU cooler during outdoor experiment and photographic images of the fabricated 3D printing models; scale bar = 1 cm. (b) Outdoor experiment temperature measurement results coated on 3D printing models (house, dome, bus); Bare 3D model (grey square), the 3D models coated with white paint (orange rhombus), and the 3D models coated with TPU cooler (green dot) (c) Graph of the relationship between the cooled temperature and the cooling form factor of the TPU cooler according to various 3D models.

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