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Emissivity and Reflectivity Measurements for Passive Radiative Cooling Technologies

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Abstract

Due to their optical properties, passive radiative cooling (PRC) materials can effectively reflect solar radiation while simultaneously dissipating heat through the infrared transparency windows using outer space as a cold and renewable heat sink. This makes it possible to achieve sub-ambient temperatures even in direct sunlight without using any electricity for cooling or air-conditioning. However, the accurate determination of these peculiar optical properties is challenging and subject to high uncertainty levels when using commercial instruments available to industrial end users and research laboratories. Within the EU project PaRaMetriC, aiming at establishing a metrological framework for the comparable performance evaluation of PRC technologies, the Physikalisch-Technische Bundesanstalt is leading a work package dedicated to the development of accurate and traceable methods to determine the infrared optical and thermophysical properties of PRC materials. These include reflectivity and emissivity in the broad spectral range from 250 nm to 50 µm, encompassing both, the solar spectrum (250 nm–2500 nm) and the infrared transparency window of the atmosphere (7.1 µm–13 µm) with a target absolute uncertainty of less than 0.03. For this purpose, several candidate benchmark passive cooling materials have been characterized by PTB in the wavelength range between 1.4 µm and 50 µm. The range 250 nm to 1.4 µm will be covered in an upcoming paper. Characterizations of, and comparisons between, reference and end-user measurement techniques applied for the measurements of selected PRC materials will not only allow accurate determination of the thermophysical properties, but also identification of measurement problems and suitable approaches in this rapidly expanding field.

Keywords Emissivity · Reflectivity · Passive radiative cooling

1 Introduction

Effective optimization and development of the passive radiative cooling (PRC) technologies are essential for addressing the global climate challenge since cooling systems are currently responsible for nearly 10% of electricity consumption and 3% of greenhouse gas emissions worldwide [1].

The increase in the number of days with extreme heat has been documented in numerous studies [2–5]. Considering the inevitable growth of the cooling needs in a warming world, and consequently the electricity consumption, the environmentally friendly PRC technologies will necessarily lead to long-term economic, social and environmental impacts. Due to their optical properties, PRC materials can effectively reflect solar radiation but at the same time dissipate heat through the infrared transparency windows, utilizing outer space as a cold and renewable heat sink. This makes it possible to achieve sub-ambient temperatures and equivalent cooling power exceeding 100 W/m^2 even under direct sunlight without using any electricity and with no consumption of water due to their non-evaporative nature [6–8]. The optimal optical properties of a radiative cooling surface are illustrated in Fig. 1 by the red curve, which shows high reflectance in the solar spectrum and emissivity close to 1 within the infrared atmospheric window.

The most promising applications of PRC materials include the cooling of buildings, photovoltaic cells, thermoelectric generation, air conditioners and power plants as well as personal thermal management. The main designs, implementation and development of passive radiative cooling and an overview of the traditional methods for characterizing and comparing radiative cooling materials and devices are in detail provided here [9–12].

The materials utilised for modern daytime radiative cooling encompass a diverse range, including photonic structures, hybrid metamaterials, organic coatings, microporous polymer films, plastic textiles and delignified wood [13, 14]. A detailed overview of the composition of various paints or materials with different fillers,

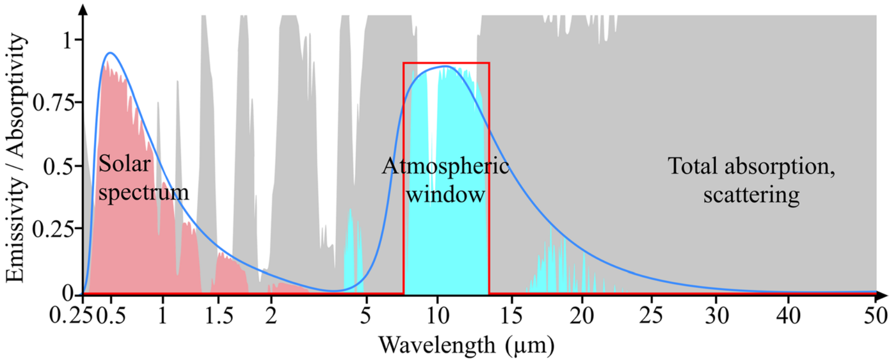


Fig. 1 The schematic for radiative cooling illustrates the ideal optical properties of a radiative cooling surface, depicted by the red curve, for optimal performance. In the solar spectrum, the surface exhibits near-zero emissivity to minimize heat absorption. Conversely, within the infrared atmospheric window, the emissivity approaches 1 to maximize thermal radiation and achieve effective cooling

nano or micro-particle as well as binders and resins, which allow to adjust its optical properties, can be found here [15–17].

2 PaRaMetriC and Cool White Projects

The further development and commercialisation of the new PRC technologies are substantially hindered by the absence of reliable test protocols for evaluating their cooling properties [18–20]. The modelling accounting for the impact of atmospheric and geoclimatic conditions, characterisation of emissivity and reflectivity over a broad wavelength range with low uncertainties, realisation of benchmark systems with known properties as well as calibration of portable instruments for on-site monitoring indicate areas that urgently require significant improvement. The development of a new conceptual framework and the adoption of highly multidisciplinary approaches are crucial steps that can facilitate the further development and large-scale application of PRC technologies.

Therefore, a three-year EU research project 21GRD03 PaRaMetriC (from 2022 to 2025) [21] is focused on establishing a metrological framework for comparable performance evaluations of PRC technologies and to classify, evaluate and rate the cooling performance of the emerging class of PRC materials. To achieve this goal, the project will systematise and improve the different and variable approaches currently adopted in the scientific literature. This process should foster the adoption of this relevant technology, potentially leading to reductions in energy and freshwater consumption. At the same time, new measurement methods and protocols aiming at standardisation for this specific class of materials and their applications will be developed. This effort aims to fill the existing gap in measurement and testing capabilities for both industry and end users.

The basis for all the above-mentioned project objectives is the accurate knowledge of the radiative properties of the investigated material, namely the reflectivity and emissivity. The main difficulty here lies in the accuracy of the available methods and the wide wavelength range involved. The measurements must be typically carried out from 250 nm to 25 μm (or even beyond, depending on the application), encompassing both the solar spectrum (250 nm to 2500 nm), where the PRC materials should exhibit highly reflective properties, and the main infrared transparency window of the atmosphere (approximately 7.1 μm to 13 μm), where the emissivity should be very high. Furthermore, the hemispherical total emissivity is required for thermal balance calculations and modeling, while the angular spectral distribution serves as the primary characteristic for assessing the quality of new materials under study.

Commercially available portable instruments such as emissometers or reflectometers for on-site measurements as well as integrating spheres in combination with Fourier Transform Infra-Red (FTIR) spectrometers are most often used for measuring the total hemispherical emissivities [22, 23]. However, measurement uncertainties and observed differences between various measurement techniques and experimental conditions are significant [24, 25] and yet typically disregarded in the recent literature studying these materials. One reason for this is a common lack of calibrated samples tailored to the specific properties of PRC materials. Additionally, the extrapolation of hemispherical total emissivity from near-normal emissivity is not well controlled in terms of uncertainty, as previously demonstrated in the EMPIR project 16NRM06 “Improvement of emissivity measurements on reflective insulation materials” (EMIRIM), which focused on the measurement of hemispherical total emissivity of reflective foils used as the thermal insulation products for buildings [26, 27]. The PRC materials, often featuring "optically structured" coatings, considering the heterogeneous types and properties or consisting of several layers, could be even more challenging and introduce larger uncertainties [28]. Moreover, the specific structures of PRC materials can diverge significantly from those of smooth opaque materials, especially concerning the angular distribution of emissivity. As noted in some studies, the full angular dependence of emissivity, which has been experimentally disregarded thus far, is key in determining net cooling power, particularly under adverse humidity and temperature conditions [29].

As the leader of a work package dedicated to the spectral characterization of PRC materials, the Physikalisch-Technische Bundesanstalt (PTB) [30], Germany’s national metrology institute, along with partners of the PaRaMetriC project, will develop accurate and traceable methods for determining the optical properties of PRC materials. This includes reflectivity and emissivity across the broad spectral range from 250 nm to 50 µm with an absolute standard uncertainty of less than 0.03. For this purpose, several candidate benchmark PRC materials have been selected and will be measured using various approaches by several partners.

Furthermore, the objectives of this work package include evaluating the long-term stability of the optical properties of PRC materials, which also requires precise emissivity and reflectivity measurements with low uncertainties to detect possible changes due to heat, contamination, water and aging. Additionally, the methods to convert directional emissivity measurements into hemispherical total emissivity will also be developed. This is crucial because most portable instruments (such as emissometers) only measure directional values, while accurate simulations and heat-balance calculations rely on hemispherical data. By providing highly accurate hemispherical emissivity data, PTB supports more reliable analyses and enhances the overall framework for evaluating PRC materials.

In this paper, the initial results of emissivity measurements of four selected samples conducted at PTB will be presented, covering a wavelength range from 1.4 µm to 50 µm. In the next phase of the project, these results will serve as reference data in the IR range for comparison with measurements obtained by other partners. Additionally, PTB together with the partners of the PaRaMetriC project is supporting an external project Cool White closely linked to PaRaMetriC [31]. The objective of this cooperation project is to develop and implement PRC technologies, with a particular focus on investigating the cooling effect of special white paints on building roofs. These white paints are being applied to several school and company roofs in Rwanda and South Africa in collaboration with local painters. The expectation is that lower temperatures resulting from this initiative will not only improve conditions for students and workers in these countries but also facilitate energy savings. PTB will bring its expertise in determining optical properties to investigate various white paints, identifying the ones most closely approximating the properties of

PRC coatings and providing training to local metrology institutes on how to install temperature and humidity measurement equipment to the building for the continuous monitoring of thermal comfort conditions before and after the application of the cool roof paints.

3 Emissivity Measurements at PTB

PTB operates two unique facilities for angular resolved measurement of directional spectral, directional total and hemispherical total emissivities under air and in vacuum. These facilities cover the spectral range from 1.4 µm to 200 µm and the temperature range from -40 °C to 1000 °C. The Emissivity Measurements in Air Facility (EMAF) [32] and the Reduced Background Calibration Facility (RBCF 2) [33] have been operated at PTB for several years and have successfully contributed to several research projects: various European projects founded by EURAMET like “Inspection Techniques for Composites in Energy Applications” (VITCEA), abovementioned EMIRIM and the project series “Metrology for Earth Observation and Climate” (MetEOC) 1 to 4. Further critical contributions were and are provided to the climate observation missions FORUM of ESA [34] and Libera of NASA [35]. Furthermore, these facilities have contributed to several national and international intercomparisons [36]. Additionally, numerous specific measurements have been performed for various partners or customers based on bilateral research or contract work.

The measurements presented in this paper were performed using the EMAF. To ensure internal verification, the vacuum measurement setup RBCF2 was used to compare the performance across both systems with a reference sample. At both setups, the measurement scheme for determining emissivity is based on a comparison of the spectral radiance of the sample against the spectral radiances of two reference blackbodies at different temperatures using a FTIR spectrometer (Fig. 2). The sample is mounted on a heater and placed inside a temperature-stabilized spherical enclosure. With the help of an evaluation model that accounts for the balance of heat fluxes at the sample surface and multiple reflections between the sample and the spherical enclosure, both the surface temperature and the directional spectral emissivity can be accurately computed [37]. To calculate the hemispherical total emissivity, a mathematical model developed and extensively validated at PTB through various comparisons was used. The model of the angular dependence of the directional emissivity is based on the sum of the Fresnel equations for both polarization directions, incorporating the complex refractive index and an offset. It is fitted to experimental data obtained from directional total emissivity measurements at observation angles of 10°, 20°, 30°, 40°, 50°, 60°, and 70°, while accounting for their associated uncertainties. Finally the hemispherical emissivity is calculated by integrating the model over the full angular range from 0 to 90°. [32].

The capabilities of the two measurement setups at PTB concerning emissivity measurements are listed in Table 1.

The uncertainty of the directional spectral emissivity is calculated via a Monte–Carlo method, which is based on the complete radiation budget. This method

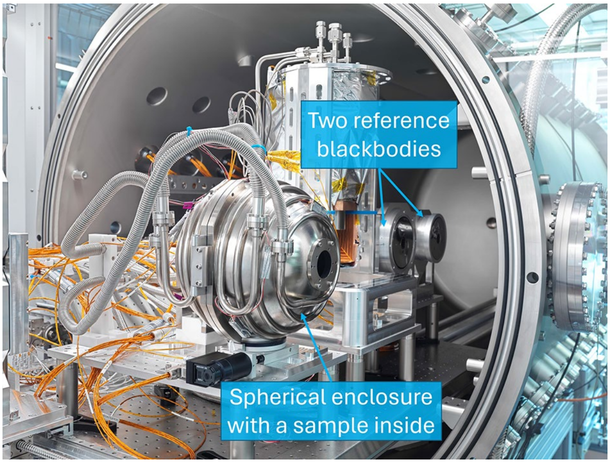


Fig. 2 Photo of the facility for emissivity measurement at PTB: two reference blackbodies and a temperature-stabilised spherical enclosure can be seen. The sample is mounted on a heater and placed inside the spherical enclosure

Table 1 Capabilities of the two measurement setups for emissivity measurements at PTB

	EMAF (air)	RBCF2 (vacuum)
Temperature range	20 °C to 500 °C	− 40 °C to 1000 °C
Spectral range	2.5 µm to 100 µm	1.2 µm to 200 µm
Pressure range and environment	Ambient pressure, dry air	10^{-6} hPa to ambient, dry air or inert gas
Angular resolved	+− 80°	+− 80°
Clean room	Normal lab condition	Clean room of class ISO5

considers every radiation contribution in the optical path and is spectrally dependent. Furthermore, the uncertainty budget is calculated for each individual measurement, as the significance of individual uncertainty contributions varies significantly depending on the conditions of the measurement and the sample investigated.

4 Experimental Conditions

To accomplish the project objectives, the reflectivity and emissivity of the PRC materials must be measured using various approaches by several partners. Consequently, determining the thermophysical properties and analysis of measurement problems and suitable approaches will be crucial for identifying the sources of deviation and the uncertainties of measurement techniques and other (both commercial and custom) instruments which are available at the partner institutes. Moreover, selecting a benchmark material from among the measured candidates and developing a set of appropriate samples for calibration will establish a better traceability for industrial and in-field measurements.

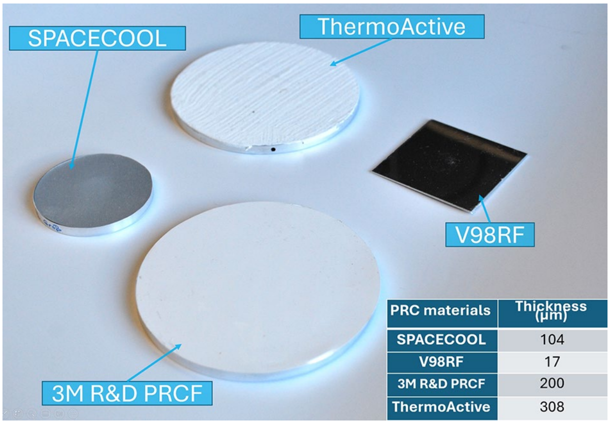
As the initial step, PTB performed measurements on selected samples using its reference setups focusing on the wavelength range from 1.4 µm to 50 µm. The resulting spectra and their uncertainties will represent the reference data against which other measurements from the partner institutes will be compared. Two experimental setups at PTB were employed for these measurements: the setup for emissivity measurements in air (EMAF) in a wavelength range from 5 µm to 50 µm and the setup for diffuse reflectivity measurements with a gold-coated integrating sphere in the spectral range from 1.4 µm to 5 µm [38]. This different approach using a commercial Bruker integrating sphere and the vacuum FTIR spectrometer was chosen here to perform additional measurements in the range below 5 µm, since the direct emissivity measurements in this wavelength range require a significantly higher temperature for the samples due to Planck's law: temperatures of 400 °C and above. However, several PRC materials are not suitable for operation at such high temperatures, given their near-ambient target application scenario.

The directional spectral emissivity was determined at slightly different nominal temperatures below 100 °C, at angles of observation from 10° to 70° with respect to the surface normal and in a wavelength range from 5 µm to 50 µm. In addition, the total directional emissivity and the hemispherical total emissivity were calculated. Two sets of detectors and beamsplitters were used with the FTIR spectrometer according to the wavelength and temperature ranges. In the range from 5 µm to 25 µm, a deuterated l-alanine-doped triglycine sulfate (DLaTGS) in combination with a potassium bromide (KBr) beamsplitter were used. In the range from 25 µm to 50 µm, the emissivity was determined using a far-infrared deuterated triglycine sulfate (FDTGS) detector in combination with a 6 µ Multilayer Mylar beamsplitter.

The gold-coated integrating sphere was equipped with a liquid nitrogen-cooled mercury cadmium telluride (MCT) detector and a KBr beamsplitter to measure the directional–hemispherical spectral reflectivity in the wavelength range of 1.4 µm to 5 µm. These measurements were conducted at room temperature using a Globar lamp as the radiation source. Each sample was then positioned at the reflectivity port inside the integrating sphere, enabling the measurement of directional–hemispherical spectral reflectivity at an incidence angle of approximately 12°.

5 PRC Benchmark Materials

Within the project, several stakeholders and companies already involved in energy-efficient building envelopes and traditional cool roof systems, or who are working towards the development and commercialization of actual PRC materials, were contacted for a preliminary evaluation of their products. For this article, four samples have been selected (Fig. 3): SPACECOOL, V98RF, 3M R&D PRCF Foil and ThermoActive. All four samples are PFAS-free.



PRC materials	Thickness (μm)
SPACECOOL	104
V98RF	17
3M R&D PRCF	200
ThermoActive	308

Fig. 3 Photo and thicknesses of the selected PRC materials: optical foil from the company SPACECOOL (5.1); joint development of Cooling Photonics and Almeco “V98RF” (5.2); the R&D developmental PRCF from 3M “3M R&D PRCF” (5.3) and white paint “ThermoActive” (5.4)

5.1 SPACECOOL

A self-adhesive multilayer silver-polymer optical film with specular reflection and surface roughness-induced light scattering from the company SPACECOOL INC. was applied to a copper substrate with a diameter of 50 mm and a thickness of 5 mm. The substrate includes a hole of 2 mm diameter to accommodate a platinum resistance thermometer (PRT), facilitating the monitoring of the substrate temperature.

5.2 "V98RF"of Cooling Photonics S.L. and Almeco Group

A selective emitting polymer “RF” developed by Cooling Photonics was applied on a silver-based mirror labeled “Vega 98®” (V98) cut to size 40 mm × 40 mm provided by Almeco Group. “Vega 98®” is a specially designed highly reflective surface. It consists in a high-purity aluminium substrate, enhanced by a specific PVD multilayer coating system based on silver. Vega 98 is manufactured on a continuous coil vacuum coating plant, which makes it a fully scalable product. The RF coating preserves the high reflectivity of the V98 substrate while providing high emissivity in the IR atmospheric window, resulting in a high-performance selective emitter (V98RF).

5.3 3M R&D PRCF

A self-adhesive metal-free white-diffuse R&D developmental passive radiative cooling foil (PRCF) provided by 3M was adhered on an aluminum substrate of

90 mm in diameter using a thermal paste Apiezon. A 2 mm hole for the PRT was also provided in the substrate.

5.4 ThermoActive

As part of the Cool White project, a commercial white paint, ClimateCoating® ThermoActive of the company SICC Coatings GmbH, was applied to a flat aluminum substrate with a diameter of 90 mm, a thickness of 5 mm, and a 2 mm hole for inserting a thermometer. The paint features a specialized dispersion containing hollow glass–ceramic bodies as aggregates. Once dried, the coating forms a reflective membrane capable of reflecting heat radiation while providing an additional cooling effect through controlled evaporation.

6 Results

The directional spectral emissivities of the four PRC materials are depicted in Fig. 4 for an angle of observation of 10° with respect to the surface normal. The red dashed line represents the boundaries of the IR atmospheric window, while

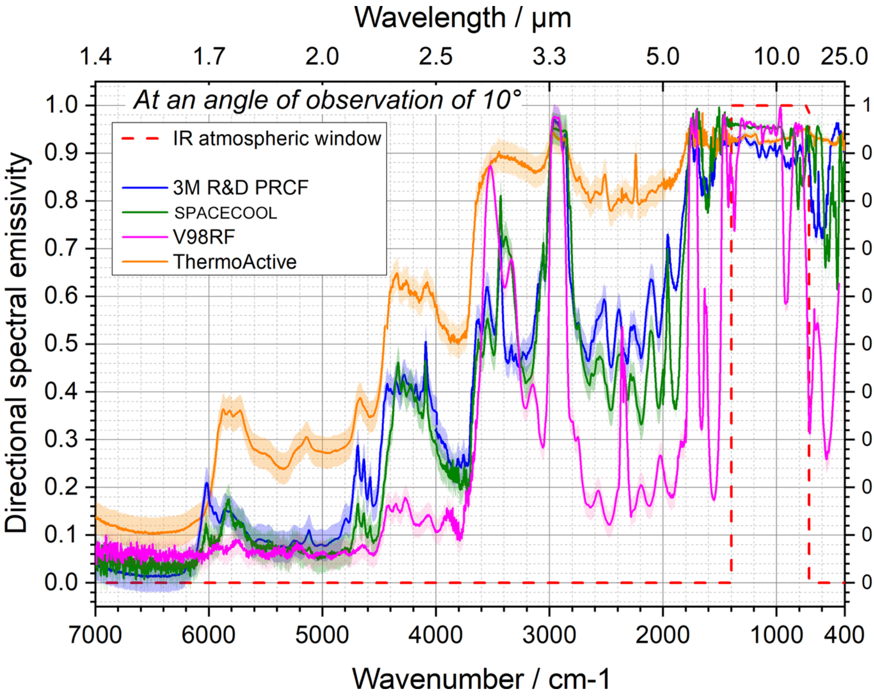


Fig. 4 Directional spectral emissivity of four selected PRC materials: shown at an observation angle of 10° with respect to the surface normal and in the range from 1.4 µm to 25 µm. The range of the standard uncertainty ($k = 1$) for each individual measurement shown as shaded areas around the curves

Table 2 Directional total and hemispherical total emissivities of four selected PRC materials in the wavelength range from 7.1 µm to 13 µm with corresponding standard uncertainties $u(\varepsilon)$

Angle	SPACE-COOL ε (60 °C)	$u(\varepsilon)$ $k=1$	V98RF ε (100 °C)	$u(\varepsilon)$ $k=1$	3 M R&D PRCF Foil ε (60 °C)	$u(\varepsilon)$ $k=1$	ThermoActive ε (80 °C)	$u(\varepsilon)$ $k=1$
10°	0.928	0.015	0.891	0.008	0.901	0.008	0.932	0.007
20°	0.933	0.014	0.889	0.008	0.898	0.008	0.931	0.007
30°	0.935	0.014	0.884	0.008	0.900	0.008	0.928	0.007
40°	0.935	0.014	0.878	0.008	0.899	0.008	0.922	0.007
50°	0.927	0.014	0.878	0.008	0.885	0.008	0.911	0.007
60°	0.899	0.015	0.856	0.008	0.846	0.009	0.887	0.007
70°	0.818	0.016	0.730	0.009	0.753	0.010	0.834	0.008
ε hem	0.889	0.015	0.834	0.008	0.846	0.009	0.885	0.007

also illustrating an ideal emissivity profile of a selective PRC material. The measurements were conducted at temperatures ranging from 60 °C to 100 °C, slightly varying based on the temperature tolerance of each material (Table 2). However, this temperature variation does not influence the results, as the emissivity of these materials remains constant within this range. Additionally, the directional–hemispherical spectral reflectivity from 1.4 µm to 5 µm is expressed here as "1—reflectivity". As noted earlier, these reflectivity measurements were performed at room temperature, as the integrating sphere setup does not require sample heating.

All measured curves demonstrate a sufficiently high level of emissivity within the IR atmospheric window containing certain individual spectral features. A notable decrease of the directional spectral emissivity is observed in the shorter infrared range (below 6 µm). As previously mentioned, the cooling performance of PRC materials depends not only on their emissive properties in the IR atmospheric window but also on their high reflectance in the solar spectrum (250 to 2500 nm). Assuming the reflectivity remains consistent with the levels observed around 1.4 µm, the performance of the investigated materials appears highly promising. However, this assumption necessitates measurements in the solar range, which will be detailed in future studies.

The integrated quantities of all PRC materials- total directional and hemispherical total emissivity- are detailed in Table 2 and illustrated in Fig. 5. The uncertainty stated here is the standard measurement uncertainty by the coverage factor $k=1$. It has been determined in accordance with the "Guide to the Expression of Uncertainty in Measurement (GUM). To evaluate the performance of these materials in the IR range, the calculation was carried out within the range of the main IR atmospheric window from 7.1 µm to 13 µm.

The directional total emissivities of the PDRC materials, along with their standard uncertainties, demonstrate high values, with a typical decrease at larger observation angles. Near-normal emissivity values of 0.9 or higher are comparable to state-of-the-art broadband high emissivity materials such as Nextel 811-21

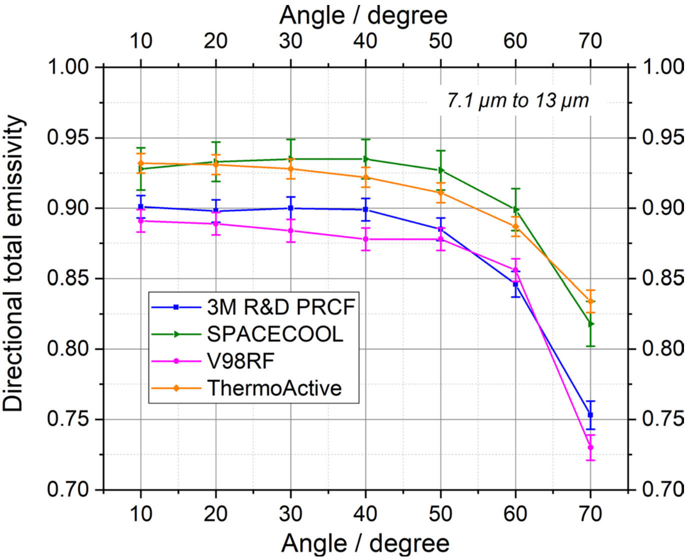


Fig. 5 Directional total emissivities of four selected PRC materials in the wavelength range from 7.1 µm to 13 µm with corresponding standard uncertainties depending on the angles of observation from 10° to 70° with respect to the surface normal

and carbon nanotube-based coatings. These levels are sufficient to ensure effective cooling via thermal radiation in the IR range.

However, determining the overall cooling suitability of these materials requires comprehensive characterization in the solar spectrum, particularly between 250 and 2500 nm. Reflectivity in this range plays a critical role, as every 1% increase in solar reflectivity translates to a reduction of approximately 10 W/m^2 in solar heat gain. Conversely, spurious solar gains of 20 W/m^2–30 W/m^2 can easily negate the cooling effect of even a perfect 100% selective emitter in the atmospheric window.

The importance of the long-wavelength emission of PRC materials is emphasised not only by the presence of an additional atmospheric window around 20 µm, which could contribute partly to more efficient cooling, but also by the efficiency of a broadband thermal emittance from 25 µm to 40 µm [8]. This is attributed to the fact that several application scenarios of PRC materials (such as the cooling of heat pumps, electronic boards, building envelopes and photovoltaic modules.) involve above-ambient temperatures due to their contact with air and self-heating. Consequently, emitters can effectively perform over the whole broadband range as selective long-wavelength infrared materials.

To optimize cooling performance, the emissivity of PRC materials should remain high not only within the atmospheric window of 7.1 to 13 µm but also extend up to 50 µm. However, it is important to note that this radiation will mostly be absorbed by water vapor and the atmosphere near the material. So a high emissivity at wavelengths longer than 13 µm will lead to better cooling performance for cold environments only. For warm environments a high emissivity above 13 µm is not desirable.

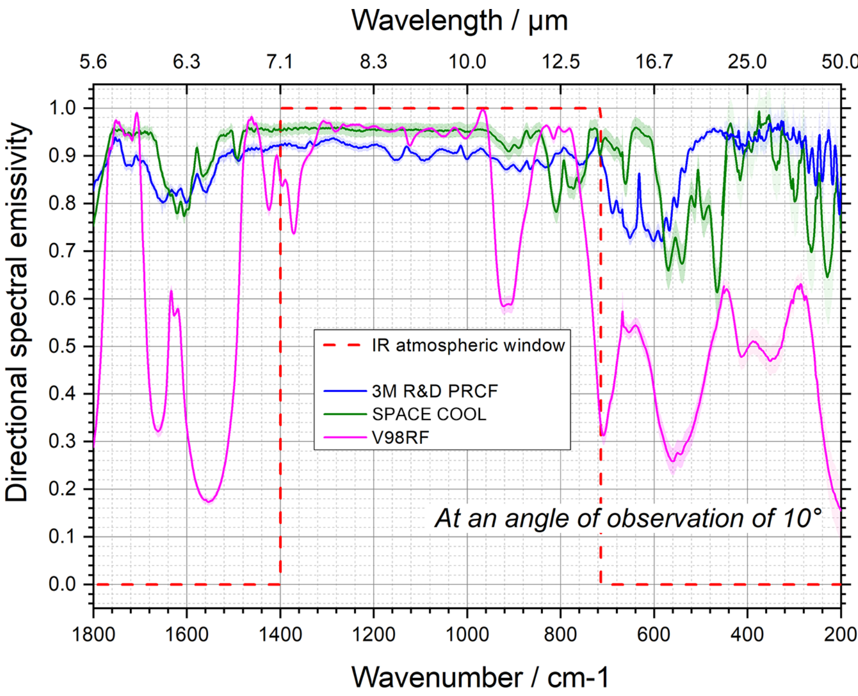


Fig. 6 Directional spectral emissivities of three selected PRC materials in the FIR range extending the data presented in Fig. 4: shown at one angle of observation of 10° with respect to the surface normal and in the range from 5.6 µm to 50 µm. The range of the standard uncertainty ($k=1$) for each individual measurement is shown as shaded areas around the curves

PTB's ability to perform far-infrared (FIR) emissivity measurements traceable to the International Temperature Scale ITS-90 made it possible to characterise the coatings in this spectral region as well. The measured emissivties of the PRC materials up to 50 µm are depicted in Fig. 6, extending the data shown in Fig. 4 into the far-IR range. Notably, two of the three samples exhibit high emissivity in the 13 to 50 µm range, indicating their significant potential for additional cooling capacity within this extended spectrum.

7 Conclusion

Within the initial phase of PaRaMetriC and Cool White projects, PTB has determined the emissivity of various modern, commercially available PRC materials in the wavelength range from 5 µm to 50 µm under various angles of observation ranging from 10° to 70°. These measurements achieved an absolute uncertainty of less than 0.016 for the SPACECOOL sample and less than 0.010 for the other three samples- joint development of Cooling Photonics and Almeco "V98RF"; the R&D developmental PRCF from 3M "3M R&D PRCF" and white paint "ThermoActive" and are traceable to the International Temperature Scale ITS-90. This result surpasses the stated uncertainty target of 0.03, providing a valuable reference that will help improve the emissivity results of other project partners.

The integrated quantities- directional total and hemispherical total emissivity- were calculated within the range of the main IR atmospheric window approximately from 7.1 μm to 13 μm. Additionally, the directional–hemispherical spectral reflectivity was measured using an integrating sphere from 1.4 μm to 5 μm.

In the next step, these PRC materials will be characterised by comparing measurement methods and setups across several partners. The characterisations and comparisons between reference and end-user measurement techniques applied for the measurements of selected PRC materials will not only allow an accurate determination of the optical properties in a broader spectrum ranging from 250 nm to 50 μm, but also the identification of measurement problems and suitable measurement methods.

The development of accurate and traceable approaches for determining the thermophysical properties, along with the establishment of protocols for on-site testing of PRC materials, will yield significant benefits across various sectors. Both the scientific community and industry will benefit from the new measurement data and the implementation of the guidelines and established protocols for the cooling performance evaluation. This advancement will effectively bridge a significant gap towards commercialisation of these materials, thus increasing the confidence and propensity of policymakers and stakeholders to invest in this field. The establishment of relevant norms and standards will also provide a realistic estimation of projected energy savings in different geoclimatic regions and building types, which will have longer-term economic, social and environmental impacts.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing Interests The authors declare no competing interests.

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References

1. Hannah Ritchie (2024) - "Air conditioning causes around 3% of greenhouse gas emissions. How will this change in the future?" Published online at OurWorldinData.org. Retrieved from: 'https://ourworldindata.org/air-conditioning-causes-around-greenhouse-gas-emissions-will-change-future' [Online Resource]
2. N. Freychet et al., Future changes in the frequency of temperature extremes may be underestimated in tropical and subtropical regions. Commun. Earth Environ. **2**, 1–8 (2021)
3. L. Ruth, Z. Stalhandske, E.M. Fischer, Detection of a climate change signal in extreme heat, heat stress, and cold in Europe from observations. Geophys. Res. Lett. **46**, 8363–8374 (2019)
4. IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press
5. M. Burke, S.M. Hsiang, E. Miguel, Global non-linear effect of temperature on economic production. Nature **527**, 235–239 (2015). https://doi.org/10.1038/nature15725
6. A.K. Stark, J.F. Klausner, An R&D strategy to decouple energy from water. Joule **1**, 416–420 (2017). https://doi.org/10.1016/j.joule.2017.10.009
7. X. Li, Zh. Ding, G.E. Lio, J. Zhao, H. Xu, L. Pattelli, L. Pan, Y. Li, Strain-adjustable reflectivity of polyurethane nanofiber membrane for thermal management applications. Chem. Eng. J. **461**, 142095 (2023)
8. E. Goldstein, A. Raman, S. Fan, Sub-ambient non-evaporative fluid cooling with the sky. Nat. Energy **2**, 17143 (2017). https://doi.org/10.1038/nenergy.2017.143
9. J. Mandal, Y. Yang, N. Yu, A.P. Raman, Paints as a scalable and effective radiative cooling technology for buildings. Joule (2020). https://doi.org/10.1016/j.joule.2020.04.010
10. X. Li, J. Peoples, Z. Huang, Z. Zhao, J. Qiu, X. Ruan, Full daytime sub-ambient radiative cooling in commercial-like paints with high figure of merit. Cell Rep. Phys. Sci. **1**, 100221 (2020). https://doi.org/10.1016/j.xcrp.2020.100221
11. J. Liu, Y. Zhang, S. Li, C. Valenzuela, S. Shi, C. Jiang, S. Wu, L. Ye, L. Wang, Z. Zhou, Emerging materials and engineering strategies for performance advance of radiative sky cooling technology. Chem. Eng. J. **453**, 139739 (2023). https://doi.org/10.1016/j.cej.2022.139739
12. M. Chen, D. Pang, X. Chen, H. Yan, Y. Yang, Passive daytime radiative cooling: fundamentals, material designs, and applications. EcoMat **4**, e12153 (2022). https://doi.org/10.1002/eom2.12153
13. W. Li, Y. Li, K.W. Shah, A materials perspective on radiative cooling structures for buildings. Sol. Energy **207**, 247–269 (2020). https://doi.org/10.1016/j.solener.2020.06.095
14. X. Yu, J. Chan, C. Chen, Review of radiative cooling materials: performance evaluation and design approaches. Nano Energy **88**, 106259 (2021). https://doi.org/10.1016/j.nanoen.2021.106259
15. X. Li, J. Peoples, P. Yao, X. Ruan, Ultrawhite $BaSO_4$ paints and films for remarkable daytime subambient radiative cooling. ACS Appl. Mater. Interfaces **13**, 21733–21739 (2021). https://doi.org/10.1021/acsami.1c02368
16. X. Li, Z. Ding, L. Kong, X. Fan, Y. Li, J. Zhao, L. Pan, D.S. Wiersma, L. Pattelli, H. Xu, Recent progress in organic-based radiative cooling materials: fabrication methods and thermal management properties. Mater. Adv. **4**, 804–822 (2023). https://doi.org/10.1039/D2MA01000C

17 L. Zhou, J. Rada, Y. Tian, Y. Han, Z. Lai, M.F. McCabe, Q. Gan, Radiative cooling for energy sustainability: materials, systems, and applications. Phys. Rev. Mater. (2022). https://doi.org/10.1103/PhysRevMaterials.6.090201

18 X. Yin et al., Terrestrial radiative cooling: using the cold universe as a renewable and sustainable energy source. Science **370**, 786–791 (2020)

19. K. Bu, X. Huang, X. Li, H. Bao, Consistent assessment of the cooling performance of radiative cooling materials. Adv. Funct. Mater. **33**, 2307191 (2023). https://doi.org/10.1002/adfm.202307191
20. L. Zhou, X. Yin, Q. Gan, Best practices for radiative cooling. Nat. Sustain. **6**, 1030–1032 (2023). https://doi.org/10.1038/s41893-023-01170-0
21. Metrological framework for passive radiative cooling technologies PaRaMetriC: https://parametric.inrim.it/home
22. J.-P. Monchau, M. Marchetti, L. Ibos, J. Dumoulin, V. Feuillet, Y. Candau, Infrared emissivity measurements of building and civil engineering materials: a new device for measuring emissivity. Int. J. Thermophys. **35**, 1817–1831 (2014). https://doi.org/10.1007/s10765-013-1442-y

23. J. Manara, M. Arduini, L. Hanssen, Integrating sphere reflectance and transmittance intercomparison measurements for evaluating the accuracies of the achieved results. High Temp.-High Pressures **38**, 259–276 (2009)
24. CEN/TC 89/WG 12 N 209: Note of internal communications between members of working group CEN/TC 89/WG 12, 2013
25. Directive 2010/31/EU: Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings, 2010. https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:153:0013:0035:EN:PDF
26. JRP EMIRIM: Improvement of emissivity measurements on reflective insulation materials: https://projects.lne.eu/jrp-emirim/

27 A. Adibekyan, E. Kononogova, J. Hameury, M. Lauenstein, C. Monte, J. Hollandt, Emissivity measurements on reflective insulation materials. Tm - Technisches Messen **88**, 617–625 (2021). https://doi.org/10.1515/teme-2021-0049

28. A. Synnefa, A. Pantazaras, M. Santamouris, E. Bozonnet, M. Doya, M. Zinzi, A. Muscio, A. Libbra, C. Ferrari, V. Coccia, F. Rossi, D. Kolokotsa, Interlaboratory comparison of cool roofing material measurement methods Proceedings of the 34th AIVC - 3rd TightVent - 2nd Cool Roofs' - 1st venticool Conference , 25–26 September, Athens 2013
29. W. Tong et al., A structural polymer for highly efficient all-day passive radiative cooling. Nat. Commun.Commun. **12**(1), 1–11 (2021)
30. I. Müller, A. Adibekyan, B. Gutschwager, E. Kononogova, S. König, C. Monte, M. Reiniger, J. Hollandt, Calibration capabilities at PTB for radiation thermometry, quantitative thermography and emissivity. DGZfP-Berichtsband BB **167**, 329–333 (2018). https://doi.org/10.21611/qirt.2018.015
31. https://www.ptb.de/cms/presseaktuelles/journalisten/nachrichten-presseinformationen/presseinfo.html?tx_news_pi1%5Bnews%5D=13362&tx_news_pi1%5Bcontroller%5D=News&tx_news_pi1%5Baction%5D=detail&tx_news_pi1%5Bday%5D=20&tx_news_pi1%5Bmonth%5D=2&tx_news_pi1%5Byear%5D=2024&cHash=aaf2cdcf005246dcd6a48dfdcfe0d3ea
32. C. Monte, J. Hollandt, The measurement of directional spectral emissivity in the temperature range from 80 °C to 400 °C at the physikalisch-technische bundesanstalt. High Temp. - High Pressures **39**, 151–164 (2010)
33. A. Adibekyan, C. Monte, M. Kehrt, B. Gutschwager, J. Hollandt, Emissivity measurement under vacuum from 4 µm to 100 µm and from −40 °C to 450 °C at PTB. Int. J. Thermophys.Thermophys. **36**, 283–289 (2015). https://doi.org/10.1007/s10765-014-1745-7
34. C. Pachot et al., in International Conference on Space Optics - ICSO 2020, 11852, 904–917, 2021, https://doi.org/10.1117/12.2599355
35. M.Z. Hakuba, P. Pilewskie, G. Stephens and the Libera Science Team: Libera – Observing and Understanding Earth's Energy Budget, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-13961, https://doi.org/10.5194/egusphere-egu21-13961, 2021
36. L. Hanssen et al., Metrologia **53**, 3001 (2016)

37 R.B. Pérez-Sáez, L. Campo, M.J. Tello, Analysis of the accuracy of methods for the direct measurement of emissivity. Int. J. Thermophys. **29**, 1141–1155 (2008)

38. A. Adibekyan, E. Kononogova, C. Monte et al., Review of PTB measurements on emissivity, reflectivity and transmissivity of semitransparent fiber-reinforced plastic composites. Int. J. Thermophys. **40**, 36 (2019)

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