Methods for rejecting daytime waste heat to outer space

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Outer space constitutes an extremely low temperature ($T \sim 4$ K) thermodynamic reservoir of boundless thermal capacity, with the potential to serve as a cold reservoir for cooling objects to sub-ambient temperatures in the daytime. For example, assuming a perfect emitter at 300 K, the theoretical black-body heat transfer rate to space can be calculated to be 450 Wm$^{-2}$ [1]. However, for terrestrial objects, the atmosphere serves as a highly effective infrared (IR) insulator, as well as a heat source via radiation, convection and conduction to the object when cooled to sub-ambient temperatures [1].

It has been demonstrated that wavelength-selective surfaces can be engineered to be highly emissive in the atmospheric window (wavelength 8–13 $\mu$m, where water vapor is less emissive) (see Fig. 1a) and minimally emissive across the rest of the spectrum, so the surface is in thermal communication with the cold outer space via radiation without interacting with the ambient temperature atmosphere [1]. These surfaces showed superior performance relative to black-body emitters in the absence of direct sunlight; however, during the day, when cooling load demands are generally the highest, cooling performance was overwhelmed by the high incident solar heat flux often in excess of 1000 Wm$^{-2}$.

Recent work by Rephaeli et al. [2] and Raman et al. [3], respectively,
conceptualized and demonstrated broadband nanophotonic-structured materials capable of cooling a surface at a rate of 40.1 Wm$^{-2}$ to a temperature 4.9$^\circ$C below the ambient temperatures under direct sunlight exceeding 850 Wm$^{-2}$ in Palo Alto, California, USA. This was achieved with an integrated photonic solar reflector and thermal emitter consisting of seven layers of HfO$_2$ and SiO$_2$ deposited on a silver mirror which was demonstrated to be 97% reflective of incident sunlight, whilst still being selectively emissive in the atmospheric window. When integrated into a hydronic cooling loop, this technology has the potential to offer supplemental cooling for buildings, thus decreasing HVAC operating expenditures [4].

New reported work by Zhai et al. [5] demonstrated a highly scalable roll-to-roll manufactured amorphous metamaterial with 8-μm diameter glass beads randomly dispersed in a polymer, layered upon a silver-coated silicon wafer (Fig. 1b), with a cooling capacity of 93 Wm$^{-2}$ under direct solar irradiance of greater than 900 Wm$^{-2}$ and an average cooling power of greater than 110 Wm$^{-2}$ over three days of continuous operation in Arizona, USA. This performance was achieved through randomly dispersed resonant polar dielectric SiO$_2$ microspheres, which are broadly emissive in the IR, within a polymer matrix of polymethylpentene (TPX), which is highly transparent within the visible solar spectrum.

A direct comparison of the performance of the above technologies cannot be made due to different geographic and climate conditions. However, the scalable roll-to-roll manufacturing approach in [5] constitutes a critical innovation on the pathway toward enabling radiative cooling for large-scale cooling loads such as residential and commercial buildings. Looking forward, integration into hydronic cooling systems, in addition to lifetime performance and degradation pathways (UV, weathering, surface fouling, oxidation) of these low-cost selective emitters must be investigated and optimized. Today, deployed cooling technologies are engineered for lifetimes measured in decades, and similar performance will be needed in a technology intended to disrupt this space.

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