

Reducing temperature swing of space objects with temperature-adaptive solar or radiative coating

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SUMMARY

Lacking the atmosphere for temperature neutralization, objects in outer space without thermal control undergo large temperature swings. Effective temperature management technologies (TMTs) are essential to avoid undesirable effects caused by extreme thermal conditions. However, existing high-performance TMTs impose additional burden on the limited mass and power budgets of spacecrafts. Very recently, temperature-adaptive solar coatings (TASCs) and temperature-adaptive radiative coatings (TARCs) emerged as novel light-weight, energy-free temperature-regulation approaches for terrestrial objects with excellent thermal performance. Here, we simulate and present the great potential of TASCs and TARCs as future passive TMTs for space objects. A case study of a geosynchronous satellite with body-mounted solar panels covered by TARC exhibits an interior temperature swing as small as 20.3 °C - 25.6 °C in an orbital period even with solar eclipses. These findings provide insight into the superior performance of TASCs and TARCs in space, and will promote their application in extraterrestrial missions.

INTRODUCTION

Temperature maintenance and regulation are vital to spacecrafts and astronauts due to the extremely hostile environments in space.^{1,2} The temperature of a space object can easily change by many hundreds of degrees (-220 °C to +220 °C) depending primarily on solar irradiance received by and heat radiated from the object,² imposing fatal threats to all components and crew (for manned space missions).^{3,4} Moreover, such high temperature swings also introduce instrumental misalignment,⁵ large noise signals^{6,7} and thermal cycling damages to mechanical structures⁸. To ensure normal operation of

components and survival of crew, massive temperature swings must be avoided by advanced thermal management technologies (TMTs).^{9,10}

Existing TMTs that have already been applied to space objects (including space crafts and spacesuits) are categorized as active and passive strategies according to their need for power input. Active TMTs — including electrical heaters,¹¹ cryocoolers,¹² thermoelectric coolers,¹³ and fluid loops¹⁴ — consume electricity to provide accurate temperature control of space objects. However, they typically require extra mass, volume, and power so they are generally only used with high heat loads in large space crafts.¹⁰ On the contrary, passive TMTs offer power-free control of temperatures and are thus favorable in power-sensitive and small space objects. However, conventional passive TMTs — such as paints and coatings,¹⁵ multilayer insulation materials,¹⁶ and sun shields¹⁷ — are limited by their static radiative heat transfer properties and thus incapable of reducing both the high and low temperature extremes in thermal cycles. Some advanced passive TMTs — like passive thermal louvers,¹⁸ deployable radiators,¹⁹ thermal switches,²⁰ and phase-change thermal storage units²¹ — have been employed for temperature-adaptive thermal control, but unfortunately, they come at the cost of high extra mass and volume. It is therefore essential to develop a high-performance passive TMT without additional mass and volume requirements.

Very recently, temperature-adaptive radiative coatings (TARCs) were invented,²²⁻²⁸ which “intelligently” and automatically adjust their thermal radiation according to surface temperatures. At high temperatures, they strongly emit thermal radiation to dissipate heat into outer space; at lower temperatures, they automatically turn off radiation to retain heat. The solar absorptivity of TARCs is temperature independent. Neither power input nor manual intervention are required during this process. Though first invented for terrestrial objects like house roofs, this emerging technology shows great potential in space applications. Such thin, flexible, light-weight, and power-free coatings are expected to dramatically reduce the temperature swings experienced by space objects.^{22,25,26}

In this work, we systematically simulated the temperature-regulation performance of temperature-adaptive coatings in space missions with three different models: (1) A two-dimensional (2D) flat surface; (2) A three-dimensional (3D) cube (regular hexahedron); (3) A geosynchronous 1U-CubeSat²⁹ orbiting Earth. In those models, temperature-adaptive solar coatings (TASCs) and temperature-adaptive radiative coatings (TARCs) were compared. TASCs work in a similar way as TARCs except that their solar absorptivity, as opposed to thermal emissivity, is switched in response to temperature change, while their thermal emissivity stays a constant. Both TASCs and TARCs significantly cut down the temperature swing as compared to the original surface of the space object that is not temperature-adaptive. Because the only thermal interaction with the environment in space is electromagnetic radiation, we found that, although the relative advantages between TASCs and TARCs vary from mission to mission, TARCs evidently outperform TASCs for Earth satellites in orbits with solar eclipses. Furthermore, we simulated the

scenarios where TASCs and TARC_s hypothetically have 100% transmission in the wavelength range of 0.4-1.1 μm so that they can cover the solar panels (SPs) of spacecrafts without influencing the SP performance.^{30,31} We revealed that the performance in limiting the temperature swing deteriorates for TASC_s, but remains nearly the same for TARC_s. The above analyses were followed by a case study where a geosynchronous CubeSat is covered by an experimentally demonstrated TARC (hereafter called a “real-TARC”) with published data.²² In-depth, transient thermal analysis of body-mounted SPs and interior satellite components were conducted, showing the extraordinary performance of TARC_s in reducing temperature swings. As such, TARC_s show great promise as a new passive TMT in space missions and offer new temperature-regulation solutions for a diverse range of space objects such as space stations, satellites, spacesuits, and even extraterrestrial bases.³²

RESULTS AND DISCUSSION

The extraterrestrial (AM0) solar spectrum³³ and a typical black-body radiation spectrum are shown in Figure 1A. Unlike the terrestrial thermal emitters that are limited in and optimized for the 8-13 μm atmospheric transparency window,³⁴ the thermal emitters in space are not spectrally limited due to the vacuum environment. As a result, the energy flux of thermal radiation is enhanced for objects in space to a level that could outweigh the solar heating, which necessitates the comparison between TASC_s and TARC_s in their temperature regulation performance in outer space.

Hence, we compared temperature swings of space objects using eight different TASC_s and TARC_s whose solar absorptivity (α) and thermal emissivity (ε) are defined as follows (see Supplemental Information, Table S3 for details):

- (1) TASC_s with a switchable α and a low ε (0.1) or a high ε (0.9).
- (2) SP-compatible TASC_s with a switchable α and a low ε (0.1) or a high ε (0.9).
- (3) TARC_s with a switchable ε and a low α (0.1) or high α (0.9).
- (4) SP-compatible TARC_s with a switchable ε and a low α (0.1) or a high α (0.9).

The switchable α of TASC_s and switchable ε of TARC_s are shown in the left and right insets of Figure 1A, respectively. The 19-27 °C temperature range for the switching transition is taken from previous work²² and the target temperature for stabilization is $T_{\text{set}}=23$ °C in the middle of the switching range (Supplemental Information, Note S1). Since spacecrafts, especially miniature satellites, are power-efficient systems equipped with large-area body-mounted SPs,³⁵ the compatibility with SPs will significantly expand the total applicable area of TASC_s or TARC_s on spacecrafts. In our simulation, SP-compatible TASC_s and TARC_s are those that have everything else the same as the normal TASC_s and TARC_s, but with 100% transmittance over the primary spectral response range (0.4-1.1 μm) of photovoltaics (PVs)^{30,31} so that they can be applied on top of SPs (Supplemental Information, Note S2). Note that in this simulation the SPs beneath SP-compatible TASC_s or TARC_s are assigned with a PV efficiency of 25% and a reflectance of 10%^{36,37}, leading to 65% of the solar energy in 0.4-1.1 μm converted into heat in SPs for SP-compatible cases. Apart from that 0.4-1.1 μm range in the SP-compatible scenario,

all TASCs and TARCs have 0% transmittance in both solar and thermal spectra. The above coatings were analyzed using three different models (Figure 1B, 1C and 1D).

We first calculated the surface temperature of a 2D board in space under solar irradiance (Figure 1B), with the top surface covered by TASC or TARC and the bottom surface completely insulated from the environment. Such a 2D board can be considered as a basic component of various 3D objects, thus providing valuable information on the behavior of more complex objects. A thermal equilibrium state is achieved when the Q_{Sun} equals Q_{TR} at the top surface:

$$\begin{cases} Q_{Sun}(\theta, T) = Q_{TR}(T) \\ Q_{Sun}(\theta, T) = H_{Sun} \times \sin \theta \times \alpha(T) \times A \\ Q_{TR}(T) = (H_{SB}(T) - H_{SB}(T_{space})) \times \varepsilon(T) \times A \end{cases} \quad \text{Equation 1}$$

where $H_{Sun} = 1367 \text{ W/m}^2$ is the solar energy heat flux for Earth satellites³⁸ and $H_{SB}(T)$ is the black-body radiation flux by the Stefan-Boltzmann's law³⁸⁻⁴⁰. With a background space temperature of $T_{space} = 2.7 \text{ K}$,^{39,40} the static surface temperature T as a function of solar altitude angle θ (Figure 2A) is calculated for all TASCs and TARCs, and the results are compared in Figure 2B and 2C (see Supplemental Information, Note S3 for more details). Note that all temperatures at $\theta=0^\circ$ are 2.7 K and thus are excluded from the plots for clarity. Most spacecraft components achieve optimal performance near room temperatures (Supplemental Information, Note S1), so we define the dimensionless figure of merit (FOM) for temperature management as

$$\text{FOM} = \frac{T_{set} \times \int_0^{\pi/2} d\theta}{\int_0^{\pi/2} |T(\theta) - T_{set}| d\theta} \quad \text{Equation 2}$$

Obviously, the FOM describes the relative extent of T deviating from T_{set} integrated over an entire period. A high value of FOM is desired as it indicates a small temperature swing in the space mission. The FOM would be equal to infinity if the temperature swing is ideally zero (T is constant and $= T_{set}$), close to 1 if the temperature is constant and near 0 K, and approaching zero if the temperature experiences a very large swing ($|T(\theta) - T_{set}| \gg 0$).

Due to the broadband thermal emission in space, the temperature swings for the cases of TASCs and TARCs are similar in Figure 2B and 2C. This differs substantially from terrestrial scenarios where solar heating power dominates over thermal radiation because the latter is limited to a narrow sky window³⁴. Another conclusion is the static ε (α) should be optimized to achieve smaller temperature swings for TASCs (TARCs): One order of magnitude change in FOM can be found between optimized and unoptimized TASCs and TARCs (Supplemental Information, Figure S3). Moreover, when temperature-adaptive coatings are made SP-compatible to cover SPs, the temperature-management performance of TASCs worsens due to the non-temperature-adaptive α in the 0.4-1.1 μm band. The FOM of TASC ($\varepsilon=0.1$ or 0.9) is decreased by a factor of 3.7 or 2.4 when SP-

compatibility is enforced.

To better identify the temperature swing of actual three-dimensional (3D) objects, we then simulated a cube whose six surfaces are all covered by identical TASCs or TARC_s (Figure 1C). The static temperature for such a cube is calculated by

$$\begin{cases} Q_{Sun}(\theta, T) + Q_{Heat} = Q_{TR}(T) \\ Q_{Sun}(\theta, T) = H_{Sun} \times (\sin \theta + \cos \theta) \times \alpha(T) \times A \\ Q_{TR}(T) = (H_{SB}(T) - H_{SB}(T_{space})) \times \varepsilon(T) \times A \times 6 \end{cases} \quad \text{Equation 3}$$

Based on the typical design of a 1U-CubeSat, the area of each surface (A) is set at 0.01 m².²⁹ Here, the CubeSat is assumed to be in the “working” mode with high power consumption throughout the simulated period, and the interior heating power (Q_{Heat}) is set at a constant 5 W.^{41,42} In our calculation, for simplicity, the sunbeam direction is in the YZ-plane (Figure 2E), i.e. it is normal to the -Y and +Z cube surfaces when $\theta=0^\circ$ and $\pi/2$, respectively.

Though Figure 2F and 2G verify that both TASCs and TARC_s help reduce the temperature swings, TARC_s excel in maintaining a smaller temperature swing because the total physical area of thermal emission (all six surfaces) greatly exceeds that of solar absorption (three surfaces at most), regardless of SP-compatibility (Figure 2H). The FOM of SP-compatible TASC ($\varepsilon=0.1$) is surprisingly 99.8% lower than that of the SP-compatible TARC ($\alpha=0.1$). Calculation details and results with other sunbeam directions can be found in Supplemental Information, Note S4.

Additionally, we conducted a more comprehensive thermal analysis by calculating the transient temperature of a geostationary 1U-CubeSat when the Earth is at the December solstice (Figure 3A). In such an orbit, the CubeSat does not experience solar eclipses. Note that in this model we do not consider the inhomogeneous temperature distribution inside the CubeSat. The orbital period of the CubeSat is ~1436 minutes, and the revolution of the Earth is not considered. The calculation starts at $t=-24$ hours, and the CubeSat is at position p_0 with a temperature of 0 °C.

The transient temperature is calculated by (see Supplemental Information, Note S5 for details):

$$Q_{Sun}(T, t) + Q_{Heat} + Q_{Albedo}(T, t) + Q_{ETR}(T, t) - Q_{TR}(T, t) = m \times c \times \frac{dT}{dt} \quad \text{Equation 4}$$

As shown in Figure 1D, apart from direct solar heating and thermal radiative cooling, the temperature of Earth-orbiting satellites also depends on the heating from the sunlight reflected by the Earth (known as albedo) as well as thermal infrared (IR) radiation emitted from Earth, both of which can be regulated by temperature-adaptive coatings.

The transient temperatures of the CubeSats covered by different TASCs or TARC_s are

depicted in Figure 3B and 3C, respectively. The results show that the performance of TARC_s in regulating the temperature around T_{set} is less sensitive to the value of the static α , while an unoptimized static ε can severely increase the temperature swing of a CubeSat covered by TASC_s. Here, a static α or ε means the α or ε does not change with temperature. Furthermore, the SP-compatibility deteriorates the temperature-regulation performance of TASC_s due to the uncontrolled solar absorptivity in 0.4-1.1 μ m, while SP-compatible TARC_s behave well even with SP-compatibility. The FOMs and extreme temperatures in Figure 3D also verify the above conclusions. Note that the FOM here is calculated by Equation 5 using the temperature data over an orbital period:

$$FOM = \frac{T_{set} \times \int_{\text{period}} dt}{\int_{\text{period}} |T(\theta) - T_{set}| dt} \quad \text{Equation 5}$$

However, as plotted in Figure 3E, it is revealed that an optimized TASC ($\varepsilon=0.6$) and an optimized TARC ($\alpha=0.4$) could have comparable FOMs. The additional advantage of TASC_s in this case comes from two aspects: (1) Earth albedo increases the amount of heat flux regulated by TASC_s; and (2) Earth thermal IR radiation decreases the cooling efficiency of TARC_s.

The above analyses are based on the absence of solar eclipse. Here, we also simulated the scenario where the 1U-CubeSat operates in the geosynchronous orbit in the ecliptic plane (Figure 3F), namely, the plane that the satellite will experience a solar eclipse during each circulation around the earth. The transient temperatures of the orbiting CubeSats covered by different TASC_s or TARC_s (Figure 3G and 3H) show that TARC_s outperform TASC_s in reducing temperature swing of spacecrafts in missions. Strikingly, the temperature swing of the CubeSat covered by the low- α (0.1) TARC is merely 0.7 °C, even with the solar eclipse at ~12 and ~36 hours. Similarly, an optimized α is necessary for the best performance of TARC_s, and SP-compatible TARC_s can still effectively stabilize the CubeSat temperature. The advantage of TARC_s over TASC_s in the presence of eclipse is verified by Figure 3J, where the FOM of an optimized TASC is 189, far lower than that of an optimized TARC (628). More results can be found in Supplemental Information, Note S6.

The transient temperature simulation with and without solar eclipses leads to the comparison between TASC_s and TARC_s in Earth orbits: (1) For space missions without solar eclipses, optimized TASC_s and TARC_s have similar performance in reducing temperature swings; (2) When the space objects are subject to eclipses, TARC_s are favorable due to their capacity of temperature regulation in the absence of solar light; (3) When used on SPs, TARC_s perform better than TASC_s; (4) In-depth comparison between TASC_s and TARC_s involves detailed information about the space missions, including the planet thermal IR radiation flux, solar light flux, etc. This is especially important for deep space missions. For example, space objects in near-Venus orbits may receive much more solar irradiance and thermal IR radiation from Venus, which adds to the advantage of TASC_s. As for near-Earth space objects, however, TARC_s are more versatile. Moreover,

the SP-compatibility is technically more feasible with TARCs. As such, in the next part we conduct an extensive investigation of transient temperatures of space objects covered by TARCs.

The previous model in Figure 3 only simulates the homogeneous temperature of a CubeSat by assuming that the entire CubeSat reaches thermal equilibrium instantaneously, with no consideration of the internal thermal resistance and resultant temperature inhomogeneity. To account for the temperature evolution of interior components and surfaces, we use a thermal model of CubeSat decomposed into seven nodes. As shown in Figure 4A, node #1-#6 are the six surfaces while node #7 represents all the core components (electronics, battery, etc.) inside the satellite (details in Supplemental Information, Note S7). The heat transfer among the seven nodes is calculated by

$$Q_i(t) = \begin{cases} \frac{T_7(t) - T_i(t)}{R_i}, & i < 7 \\ \sum_{j=1}^6 \frac{T_j(t) - T_7(t)}{R_j}, & i = 7 \end{cases} \quad \text{Equation 6}$$

where Q , T , t , R are the heat transfer power, temperature, time, and thermal resistance, respectively. The initial conditions are the same as those for Figure 3.

As shown in Figure 4B and 4C, the interior components of the CubeSat are effectively protected from temperature swings by a real-TARC: the temperature swing is only 2.6 °C in an orbital period of the CubeSat. As a comparison, when the two non-switching references are used (see Supplemental Information, Table S3 for details), the temperature of node #7 goes extreme, fluctuating by 15.9 °C or more around a baseline temperature as high as 79 °C or as low as -30 °C. The FOM for the real-TARC is 107.3 to 136.2 times higher than those of the references, and the influence of solar eclipses is negligible with real-TARC. If the CubeSat is completely covered by SPs and SP-compatible coatings, real-TARC can still restrict the temperature swing down to the range of 20.3-25.6 °C, far lower than those of interior satellite components in some real space missions (see Supplemental Information, Table S2). In Figure 4D, we plotted the FOMs and temperature swings of all six exterior surfaces where SP-compatible coatings are used. With SP-compatible real-TARC equipped, the surface temperatures stay within 19.5-28.7 °C, thus efficiently protecting the satellite structures from thermal fatigue damages. Since SPs may benefit from lower temperatures for a higher PV efficiency,⁴³ an ideal thermal design could simultaneously have room-temperature interior components and low-temperature exterior SPs, which can be achieved by decreasing the T_{set} of TARC while optimizing the thermal resistances of the satellite (Supplemental Information, Note S8).

TARCs can be realized by phase-change materials (PCMs) such as vanadium dioxide, whose thermal IR properties undergo a reversible, fast, and drastic change upon temperature change crossing its phase-change temperature.⁴⁴⁻⁴⁷ The target temperature T_{set} is set by the phase-change temperature of PCMs, which can be engineered by

doping,⁴⁸ strain engineering,⁴⁹ etc. Desired ε and α of TASCs and TARC s can be engineered and tuned using artificial photonic structures, respectively.^{22,27,50} Two existing challenges in this field are: (1) TARC s were only experimentally demonstrated very recently, and existing designs have not been tested in space conditions.²² (2) The realization of SP-compatible TASCs and TARC s is an extremely ambitious and challenging task that requires groundbreaking photonic design and material engineering. Experimental realization of a functional TASC with a large α tuning range is yet to be demonstrated. Experimental implementation of TASCs and TARC s in space is yet to be achieved.

In conclusion, we systematically and theoretically analyzed the temperature-management performance of temperature-adaptive solar (TASC) or radiative (TARC) coatings for three thermal system models in outer space, eight TASCs or TARC s with different technical parameters, and one case study using data of experimentally realized TARC. It is found that, though both TASCs and TARC s significantly stabilize the temperature of space objects, TARC s perform significantly better than TASCs due to the broad spectral range for thermal radiation in space, as well as larger physical surface area for thermal emission than for solar absorption. Furthermore, when the temperature-adaptive coatings are designed to be spectrally compatible to solar panels, they (especially TARC s) bring great advantages in temperature management without sacrificing the solar power generation of space objects. As a result, the thin, light-weight and cost-effective TARC s show great promise as the future passive TMT for space missions with exceptional temperature stabilization capabilities.

Experiment Procedures

Resource availability

Lead contact

Further information and requests for resources and materials should be directed to and will be fulfilled by the lead contact, Junqiao Wu (wuj@berkeley.edu).

Materials availability

This study did not generate new unique reagents.

Data and code availability

The data presented in this work are available from the lead contact upon reasonable request.

Supplemental Information

Supplemental information can be found online at

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Author Contributions

K.D. and J.W. conceived the idea. K.D., D.T., J.L., S.W., and J.Y. conducted the modeling and simulation. K.D. wrote the manuscript with assistance from other authors. All authors reviewed and revised the manuscript.

Declaration of Interests

The authors declare no competing interests.

Figure 1. Theoretical schemes

(A) Spectra of AM0 solar irradiance (left) and black-body radiation at 23 °C calculated by Planck's law (right). The red and blue boxes indicate the ideal 100% transmission band for TASCs or TARCs covering solar panels and the atmospheric transmission window for terrestrial thermal emitters, respectively. Inset: Temperature-adaptive solar absorptivity of TASCs (left) and temperature-adaptive thermal emissivity of TARCs (right) analyzed in this work.
(B-D) Schematic diagrams of the 2D board model (B), the 3D cube model (C), and the CubeSat model (D). Q_{Sun} , Q_{TR} , Q_{Heat} , Q_{Albedo} , Q_{ETR} are heat transfer power from solar irradiance (heating), thermal radiation of the CubeSat (cooling), interior satellite components (heating), Earth albedo (heating), and thermal radiation of Earth (heating), respectively.

Figure 2. Fundamental thermal analysis models for TASCs and TARCs

(A) A schematic diagram of the 2D board model.
(B and C) Static surface temperatures as a function of θ for boards covered by TASCs (B) or TARCs (C), where SP represents SP-compatible.
(D) Extracted FOMs for the cases in (B) and (C).
(E) A schematic diagram of the 3D cube model.
(F and G) Static surface temperatures as a function of θ for cubes covered by TASCs (F) or TARCs (G), where SP represents SP-compatible.
(H) Extracted FOMs for the cases in (F) and (G).

Figure 3. Transient thermal analysis of a 1U-CubeSat covered by TASCs or TARCs.

(A) A schematic diagram of the geostationary CubeSat model when the Earth is at the December solstice.
(B and C) Transient temperatures of the CubeSat covered by TASCs or TARCs.
(D) Extracted FOMs and extreme temperatures for the cases in (B) and (C).
(E) FOMs as functions of static ε (or α) for TASCs (or TARCs) for the orbit in (A).
(F) A schematic diagram of the geosynchronous CubeSat model in the ecliptic plane.
(G and H) Transient temperatures of the CubeSat covered by TASCs or TARCs.
(I) Extracted FOMs and extreme temperatures for the cases in (G) and (H).
(J) FOMs as functions of static ε (or α) for TASCs or TARCs for the orbit in (F).

Figure 4. In-depth thermal analysis of solar panels and interior components of a geosynchronous CubeSat covered by TARC in the ecliptic plane

(A) An exploded diagram of the CubeSat (left) and the corresponding thermal resistance circuit (right).
(B) Transient temperatures of node #7.
(C) Extracted FOMs and extreme temperatures of node #7.
(D) Extracted FOMs and extreme temperatures of nodes #1-#6.

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