Postprint: Temperature Measurement Study on Radiative Coatings for Ground-based Solar Telescopes

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Date: 2017-10-20T00:00:00+00:00

Abstract

During observation operations, ground-based solar telescopes and their surrounding facilities are heated by solar radiation. The heated surfaces warm the air in the vicinity of the telescope' s optical path, generating near-surface air turbulence that consequently degrades image quality. The primary approach to mitigating near-surface atmospheric turbulence involves suppressing the temperature differential between the surfaces of solar telescopes and surrounding facilities and the ambient air. A feasibility study on the use of radiative coatings to suppress heating in ground-based solar telescopes and their surrounding facilities was conducted based on measured temperature data of coating surfaces and ambient air. The results indicate that the selected radiative coating exhibits a certain capacity to reduce the temperature difference between object surfaces and ambient air. Compared with water cooling, radiative coatings offer advantages including effective temperature control and broad applicability, rendering them suitable for surface temperature management of ground-based solar telescopes and surrounding facilities.

Full Text

Temperature Measurement Study of Radiation Coatings for Ground-Based Solar Telescopes

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Abstract

During observation operations, ground-based solar telescopes and their surrounding facilities are heated by solar radiation. The hot surfaces heat the air near the telescope’ s optical path, forming near-surface air turbulence that degrades image quality. The primary method for mitigating near-surface atmospheric turbulence is to suppress the temperature difference between the surfaces of solar telescopes and surrounding facilities and the ambient air. Based on actual temperature measurements of radiation coating surfaces and air, this paper presents a feasibility study on using radiation coatings to suppress heating of solar telescopes and surrounding facilities. The research shows that the selected radiation coating has a certain ability to suppress temperature differences between object surfaces and air. Compared with water cooling, radiation coatings offer advantages such as better temperature control effects and wider applicability, making them feasible for temperature control of ground-based solar telescope and surrounding facility surfaces.

Keywords: Solar telescope; Atmospheric turbulence; Seeing; Coating

1. Introduction

Ground-based solar telescopes are the primary observational instruments for solar physics research. Modern ground-based solar telescopes leverage their large aperture advantages for high spatial resolution imaging and spectroscopic observations. However, due to the Earth’ s atmosphere, turbulent atmospheric interference significantly compromises the telescopes’ high-resolution observation capabilities. Under solar radiation, ground-based solar telescopes and surrounding facilities are heated, forming convective turbulence. Controlling surface heating of telescopes and surrounding facilities is crucial for improving the imaging quality of ground-based solar telescopes.

In astronomy, the degree of image quality degradation experienced by ground-based telescopes due to atmospheric turbulence is called “seeing.” Seeing represents the integrated image quality degradation caused by all turbulent air in the optical path. If seeing is divided into two components—near-surface seeing caused by ground-level air and seeing caused by other atmospheric layers—the full width at half maximum (FWHM) of the atmospheric seeing disk can be expressed as [1]. Near-surface air, due to large temperature fluctuations, makes the near-surface seeing caused by heating of ground-based telescope and facility surfaces non-negligible for overall seeing quality, potentially even dominant [2-3]. Since building surfaces and ancillary facilities vary among telescopes, their effects on near-surface turbulence differ. Studies on the effects of surfaces such as water on seeing indicate that the temperature difference between object surfaces and air is an important factor affecting near-surface seeing [4-7]. Research shows that mirror seeing is proportional to the surface-air temperature difference raised to the 5/3 power, and under convection, mirror seeing is proportional to the 3/5 power of the temperature difference. The smaller the temperature difference, the better the mirror seeing. For the Advanced Technology Solar Telescope (ATST), the mirror seeing is less than 0.15 when the mechanical structure surface temperature differs from air temperature by -0.5 to +0.2°C in windless conditions [2,6-7]. From these results, we can infer that minimizing the temperature difference between ground objects and air is the optimal method for reducing near-surface turbulence intensity and improving near-surface seeing.

Methods for suppressing temperature differences between telescope and facility surfaces and air are divided into passive and active thermal control. Passive thermal control lacks automatic temperature regulation capability, primarily suppressing temperature differences through thermal conduction, convective heat transfer, and selective surface radiation properties. Active thermal control mainly suppresses temperature differences through circulating coolant or air. Domestic multi-channel solar magnetic field telescopes and the Optical and Near-Infrared Solar Eruption Tracer (ONSET) mostly use white paint to suppress temperature differences. Internationally, the Swedish 1-m Solar Telescope (SST), New Solar Telescope (NST), and GREGOR also widely adopt white paint and other passive thermal control measures for their domes and building surfaces. The domeless solar telescope at Hida Observatory in Japan uses water-cooled aluminum panels on the backside to reduce building surface-air temperature differences [8]. Solar telescope buildings and rooftops have been designed with water cooling systems to cool wall surfaces. However, both active thermal control systems lack precise cooling water temperature control based on building surface and air temperature changes, resulting in less-than-ideal temperature control performance.

With the rapid development of radiation cooling coating technology, new solar telescopes have pioneered passive thermal control designs based on novel radiation coatings for their domes and tubes, such as GREGOR and the 1.8-m telescope at the Chengdu Institute of Optics and Electronics [9-10]. These coatings have high solar radiation reflectivity and thermal emissivity. Measurements of mechanical structure surfaces show that dusty coating surfaces have temperatures above air temperature. If applied to telescope building and surrounding facility surface temperature control, combined with surface air convective heat transfer, the coating can effectively suppress the temperature difference between coating and air, maintaining the temperature difference mostly within -0.5 to 1°C [3-4]. As a passive thermal control method for suppressing temperature differences, radiation coatings require further understanding of their long-term temperature control characteristics and whether outdoor environmental aging affects temperature difference suppression.

2. Experimental Setup

To study the coating’ s outdoor temperature difference suppression capability and its long-term variation, temperature measurement experiments were conducted on the cement surface of a solar telescope’ s surrounding rooftop, rooftop water pool surface, tube front, and air. The radiation coating used is a novel cooling coating that integrates solar radiation reflection, self-thermal radiation dissipation, and hollow microsphere insulation. The coating' s solar radiation absorptivity is approximately 0.1, and its thermal emissivity is approximately 0.9. The coating reflects most solar radiation while radiating accumulated heat through its own thermal radiation. Hollow ceramic microspheres in the coating form an insulating layer that blocks inward heat conduction.

2.1 Measurement Methods

To improve measurement accuracy, different temperature measurement designs were employed for different objects. Temperature measurement accuracy and frequency are shown in . Water temperature probes were placed 20 mm below the surface to reduce wave effects, with sun shields above to minimize solar radiation impact on measurements. Coating and water temperature probes were embedded in the coating and water respectively. Cement temperature probes were placed in thermal silicone drops applied to the cement surface; given the extremely high thermal conductivity of the drops, the temperature difference between cement surface and drop was minimal. Small, low heat capacity temperature probes were used to improve accuracy. Physical photos of temperature sensors are shown in [Figure 1: see original paper].

3. Experimental Data Analysis

3.1 Daily Temperature Variation of Coating and Air

Temperature data from the coating and air show similar daily temperature and temperature difference patterns. Using a typical solar telescope observation day as an example, [Figure 2: see original paper] shows the temperature curves of coating surface and air. Before 11:00, coating temperature was below air temperature. As solar radiation intensified, the coating heated up and gradually exceeded air temperature, peaking around 14:00-15:00, then gradually falling below air temperature. Temperature variation trends on other days were similar, but with significant differences in temperature differences and fluctuations.

During the three-month measurement period, the coating surface-air temperature difference was mostly concentrated within ±1.5°C, with maximum fluctuations of 3-4°C. Comparative measurements show the coating' s temperature difference suppression capability far exceeds that of white tiles, white aluminum-plastic panels, wood, and stainless steel. The coating surface and air temperature difference remained within -0.5 to 1°C for most of the time, demonstrating the coating' s ability to maintain near-air temperature.

3.2 Long-term Variation of Coating-Air Temperature Difference

During telescope operation, radiation coatings under solar radiation experience aging and dust accumulation over time. Aging and dust-induced radiation performance degradation affect the coating' s temperature difference suppression capability to some extent. If coating surface aging is too rapid or dust impact is significant, maintenance frequency increases, substantially raising usage costs and potentially requiring feasibility reevaluation.

To analyze long-term changes in the coating's temperature difference suppression capability, daily average values and RMS values of temperature differences were used as indicators. As shown in [Figure 3: see original paper], during the measurement period, the daily average temperature difference ranged from -2.96 to 1.71°C, with 47.5% of days having average differences within ±0.5°C. The RMS value ranged from 0.21 to 3.05°C, with RMS values less than 1.5°C accounting for 84.1% of days. This indicates the outdoor coating' s temperature difference suppression capability showed no significant change, demonstrating high feasibility for applying radiation coatings to telescope building and facility surfaces.

3.3 Daily Variation of Roof Cement-Air Temperature Difference

During solar telescope observation, as solar radiation intensifies, the large cement rooftop surface behind the telescope is heated by solar radiation. Temperature measurement experiments show the cement surface temperature quickly rises from below to above air temperature. The cement-air temperature difference variation curve is shown in [Figure 4: see original paper]. Measured differences reached 8-12°C, with the rooftop cement surface having a strong heating effect on the air above. Due to daily weather variations, the timing of peak temperature and maximum difference values varied significantly.

3.4 Measured Analysis of Rooftop Water Pool-Air Temperature Difference

To suppress cement surface heating, a rooftop water pool was designed for water cooling temperature control. The 1-m solar telescope' s pool has an average water depth of about 80 mm. During operation, the pool surface temperature remained significantly below air temperature most of the time, indicating less-than-ideal temperature difference suppression. Measurements of temperature differences between rooftop pools of different depths and air were conducted to evaluate water pool temperature difference suppression capability.

As shown in and [Figure 5: see original paper], measurement results indicate that larger water volume makes the water surface temperature more below air temperature with smaller fluctuations. The 20 mm water surface temperature was closest to air temperature but still inferior to the coating. The 30 mm water surface temperature remained below air temperature throughout the measurement period. Solar radiation could not heat water surfaces above 30 mm depth to exceed air temperature, confirming the coating' s ability to maintain near-air temperature for extended periods.

4. Performance Comparison Between Water Cooling and Coating Temperature Control

The 1-m solar telescope' s active water cooling system attempts to achieve near-air temperature through solar radiation heating and automatic water replenishment. However, the active thermal control system struggles with precise cooling water temperature control, and the temperature difference suppression effect is not ideal.

A performance comparison between active water cooling and radiation coating is presented in . The radiation coating tested demonstrates good capability to maintain near-air temperature, meeting ground-based solar telescope requirements for surrounding thermal environment control. Compared with water cooling, radiation coating is a feasible passive thermal control method offering effective temperature difference suppression, wide applicability, and no impact on telescope observations. Water cooling systems require precise control of water replenishment methods and temperature, with high control difficulty and costs, and water vapor affects mid-to-far infrared observations. Radiation coatings can be applied to various heated facility surfaces around ground-based solar telescopes, including wind shields near tubes, piers, building exteriors, and rooftop areas subject to rain exposure.

5. Conclusion

The temperature measurement study demonstrates that radiation coatings can effectively suppress temperature differences between solar telescope surfaces and ambient air. The coating maintains surface temperatures close to air temperature through high solar reflectivity and thermal emissivity, providing a passive thermal control solution superior to traditional water cooling systems in terms of effectiveness, applicability, and operational simplicity. The long-term measurements confirm stable performance without significant degradation, establishing radiation coatings as a viable and cost-effective method for thermal control of ground-based solar telescopes and their surrounding facilities.

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Tables:

The measurement accuracy vs. frequency for the temperature measuring experiment

The mean value and the RMS of the temperature differences between the surface of water with different depth and the air

The performance comparison between the radiation coating layer and the active water-cooling

Figures:

[Figure 1: see original paper] The actual picture of temperature sensors

[Figure 2: see original paper] The temperature curves of the coating layer and the air

[Figure 3: see original paper] The curves of the average daily and RMS of the temperature differences between the coating layer and the air

[Figure 4: see original paper] The curve of air temperature difference over the NVST roof and the cement surface

[Figure 5: see original paper] The temperature difference curves of the air and the surface of the cistern with different depth

Note: Figure translations are in progress. See original paper for figures.

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