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Passive control of the temperature homogeneity for the primary mirror surface of large ground-based solar telescopes

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Abstract. Mirror seeing effect and thermal deformation are two major effects brought by sunlight radiation to large ground-based solar telescopes, which compromise the imaging quality. To mitigate the effects, a thermal control system (TCS) is required for the primary mirror of large ground-based solar telescopes. Several studies, including ours, have discussed the TCS, about how to control the temperature difference between the primary mirror surface and the ambient air. But few of them refer to the temperature homogeneity control for the mirror surface. The temperature inhomogeneity across the mirror surface introduces thermal deformation of high spatial frequency, which cannot be compensated for through defocus aberration. So it is important to achieve the temperature homogeneity across the mirror surface. We propose a passive method to control the temperature homogeneity for the mirror surface. First, a model is built to estimate the temperature differences across the mirror surface under different cooling conditions. Based on the model, we make an estimation of the parameters of the TCS under given temperature homogeneity requirement for the mirror surface. The estimation should make a good reference for the TCS design of large ground-based solar telescopes. Then, based on the 60-cm prototype of open solar telescope (POST), we make a numeric analysis and experimental validation of the model and obtain a proper engineering coefficient of about 2.42 in the experiment. Finally, with the proposed model, we estimate the parameters and performance of the TCS for the 1.8 m Chinese large ground-based solar telescope (CLST). The results show that the velocity uniformity of the 297 air flows in the TCS for the CLST should be better than 4.86% when the temperature homogeneity requirement across the mirror surface is within ±0.5°C. [DOI: 10.1117/1.JATIS.5.4.044007]

Keywords: temperature homogeneity; mirror seeing; primary mirror; ground-based solar telescope.

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1 Introduction

Promoted by the requirements of solar physics studies and space weather forecasting, large ground-based solar telescopes have been developing quickly.[1] Larger solar telescopes can reveal finer solar activities and carry out photo starved polarization measurements, which is crucial in estimating the magnetic fields distribution and strength in the solar active regions.[2,3] The functioning large ground-based solar telescopes include the 1.6-m McMath-Pierce (MMP) solar telescope,[4] the 1.5-m GREGOR solar telescope[5] and the 1.6-m Goode Solar Telescope (GST).[6] Moreover, the 4-m Daniel K. Inouye Solar Telescope (DKIST),[7] the 4-m European Solar Telescope (EST),[8] the 2-m National Large Solar Telescope (NLST)[9] and the 1.8-m Chinese Large Solar Telescope (CLST)[10] are under construction or in the planning stage. Generally large ground-based solar telescopes utilize open structure, and thermal control systems (TCSs) are required for the primary mirrors to mitigate mirror seeing effect and thermal deformation at the mirror surface. Several studies, including ours, have discussed the TCS, about how to control the temperature difference between the primary mirror surface and the ambient air.[11–14] But few of them refer to the temperature homogeneity control for the mirror surface. When the temperatures across the mirror surface are homogeneous, the thermal deformation is uniform and the defocus aberration is obvious, making them compensable by adjusting the position of the secondary mirror or the focus. On the contrary, when the temperatures are inhomogeneous, thermal deformation of high spatial frequency is introduced, which cannot be compensated directly. This increases correction workloads of the solar adaptive optics system.

So it is important to achieve the temperature homogeneity across the primary mirror surface. Emde et al. first raised this concern and proposed an active method to control the temperature homogeneity by adjusting the air flow rate of each nozzle with a valve.[15] The finite element analyses of the method suggested that the temperature homogeneity at the SiC primary mirror surface could be controlled within ±0.1°C when the differences of the air flow rates of the nozzles was within ±5%. But in the experiment, the deviation of the flow rates only reached within ±10%, which implied the method needed further improvement. These studies were important and pathbreaking, especially for the development of large ground-based solar telescopes. However, there are still issues that have not been elaborated on with the TCS design of large ground-based solar telescopes, such as how to achieve the temperature homogeneity across the primary mirror surface and how to estimate the critical requirement of the TCS parameters in its design stage with given temperature homogeneity requirements, etc.

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In this paper, we try to resolve these two issues and propose a passive method to control the temperature homogeneity across the primary mirror surface. The core of our method is to ensure a consistent cooling condition across the mirror surface. We build a mathematic model to describe the relationship between the temperature homogeneity across the mirror surface and the standard deviation of the air flow rates of all the nozzles. On the POST, a 60-cm solar telescope, we validate the feasibility of the proposed model and estimate the engineering coefficient through experiments. Then, we apply the model and the estimation method to the CLST and estimate the parameters of its TCS under given temperature homogeneity requirement. Our studies also can be referred to in the TCS design of other large ground-based solar telescopes.

This paper is organized as follows: in Sec. 2, we proposed a new mathematic model of temperature homogeneity control with detailed derivation; in Sec. 3, we validate the feasibility of the model on the POST and estimate the engineering coefficient through experiments; in Sec. 4, we apply the proposed model to the TCS for the CLST and estimate its parameters and performance of the temperature homogeneity control; we make a conclusion and discuss our future work in Sec. 5.

2 Mathematic Model for Temperature Homogeneity Control

In our previous studies,[13] the thermal response equation [Eq. (1)] and the thermal control equation [Eq. (2)] of a TCS system were deducted in detail. The parameters of a TCS satisfy

$$T_s - T_a = \frac{\eta\rho\left(\frac{l}{\lambda_c}+\frac{1}{h_f}\right)+(T_f-T_a)}{h_n\left(\frac{l}{\lambda_c}+\frac{1}{h_f}+\frac{1}{h_n}\right)}, \tag{1}$$

and the thermal control requirement satisfying $T_s \to T_a$ can be presented as

$$T_f = T_a - \eta\rho\left(\frac{l}{\lambda_c}+\frac{1}{h_f}\right). \tag{2}$$

The parameters listed in Eqs. (1) and (2) are shown in Fig. 1 and h_f can be calculated as[16]

$$h_f = \frac{\lambda_a (Nu_d)_m}{d} = \left[2Re_d^{0.5}Pr^{0.42}(1+0.005Re_d^{0.55})^{0.5} \times \frac{1-1.1d/r}{1+0.1(H/d-6)d/r}\frac{d}{r}\right]\frac{\lambda_a}{d}. \tag{3}$$

In Eq. (3), $(Nu_d)_m$ is the average Nusselt number; $Re_d = V_f d/v$ is the Reynolds number with characteristic length d; Pr is the Prandtl number of air; λ_a and λ_c are the thermal conductivity of the air flow and the face sheet of the primary mirror, respectively; V_f is the air flow velocity at the tip of an inflow nozzle (IN); v is the dynamic viscosity; h_f and h_n are the heat transfer coefficients of the forced and natural air convection, respectively.

For acquiring the homogeneous temperature across mirror surface, one should keep the same time constant at different regions of the face sheet of the primary mirror, which is influenced by the uniformity of solar radiation, Φ_s, natural convection, Φ_n, thermal conduction of face sheet, Φ_c and forced convection, Φ_f across mirror blank, as shown in Fig. 2. The simplest mind is to keep the same conditions for various factors at different regions of the mirror blank, which is easier than adjusting the different parameters of these influencing factors. For a certain primary mirror, the external conditions should be same at different positions across the face sheet including solar radiation, ρ, air temperature, T_a, homogeneous coating, η, ambient air velocity, and so on, which will lead to the same value of Φ_s and Φ_n. Thermal conduction in face sheet is relevant to the kind of material, λ_c, thickness, l, area (i.e., pocket size), and the temperature on backside, T_b, and frontside, T_a, of the face sheet. For a unitary face sheet, homogeneous property at different positions is one of the basic demands, and the uniform parameters on structure of mirror blank can be designed and manufactured easily such as the same thickness, l, same pocket size, and so on. The homogeneity of temperature across mirror surface will be decided mainly by heat transfer coefficient, h_f, of the forced air. As shown in Eq. (3) and in Fig. 1, the height from nozzle tip to backside of face sheet, H, the diameter of IN, d, and the pocket size, r, can be designed and manufactured as the same value at different positions of the mirror blank, and (Pr, v) are uniform various relevant to only air temperature. Thus, the core problem for acquiring homogeneous temperature across mirror surface is how to ensure the uniformity of the velocities at the tip of INs.

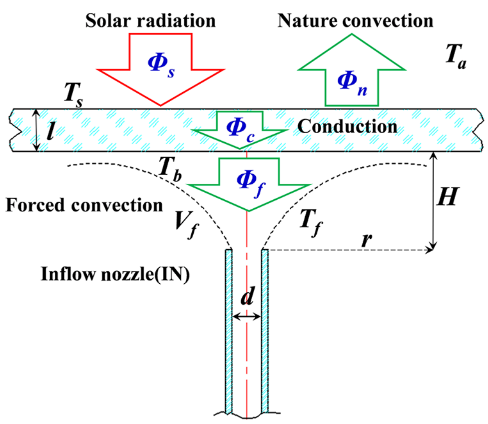


Fig. 1 Illustration of the cooling process of an air flow. T_s, temperature of the mirror surface; T_b, temperature of the back of the face sheet; T_a, temperature of the ambient air; d, in-circle diameter of the IN; H, distance from the INs tip to the bottom of the face sheet; l, thickness of the face sheet.

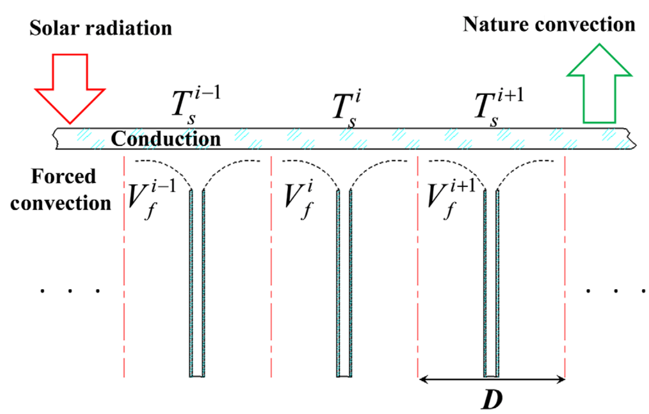


Fig. 2 Illustration of the differences between the air flow velocities of the INs, and the influence on the temperature of the mirror surface at associate positions. V_f^i, air flow velocity at the tip of the i'th IN; T_s^i, temperature of the mirror surface at the i'th IN.

In another word, a homogeneous temperature across mirror surface can be achieved by ensuring the uniformity of the velocities at the tip of all INs, and the precondition is that the parameters of the other influence factors (i.e., H, d, l, ρ, η, r, etc.) should keep the same values at different regions of mirror blank.

For a certain solar telescope, (l, r, H, d) are constants and $(\lambda_a, \lambda_c, Pr, v)$ are slowly varying, which can be treated as constants under proper condition. Thus, the heat transfer coefficient h_f can be presented as a function of the air flow velocity V_f at the tip of an IN, and Eq. (3) can be rewritten as

$$h_f\{V_f\} = \frac{\lambda_a}{d}\left[2Pr^{0.42}\frac{1-1.1d/D}{1+0.1(H/d-6)d/D}\frac{d}{D} \times\sqrt{\frac{V_f d}{v}+0.005\left(\frac{V_f d}{v}\right)^{1.05}}\right]. \tag{4}$$

The air flow velocity V_f of a certain IN is constant and measurable when a fixed frequency ventilator is employed. Ideally, the air flow velocity V_f of all the INs should be the same. But practically, asymmetric brought in by design, manufacture, integration, etc., introduce differences between the air flow velocities of the INs.

As shown in Fig. 2, differences between the air flow velocities of the INs result in temperature inhomogeneity across the mirror surface. In a practical TCS, the control parameters can be estimated by the average air flow velocity of all the INs, which is described as

$$\overline{V_f} = \frac{1}{N}\sum_{i=1}^{N} V_f^i = \frac{1}{N}\frac{1}{\pi(d/2)^2}\Omega(P), \tag{5}$$

where V_f^i is the air flow velocity of the i'th IN; $\Omega(P)$ is the flow rate of the equipped ventilator at air pressure P; N is the amount of the INs.

The air flow velocity of each IN can be presented as

$$V_f^i = \overline{V_f} + \Delta V_f^i, \quad \text{here} \sum_{i=1}^{N}\Delta V_f^i = 0, \tag{6}$$

where ΔV_f^i presents the fluctuation of air flow velocity of the i'th IN to the average.

Put Eq. (6) into Eqs. (4) and (1), we get Eq. (7) which calculates the temperature of the mirror surface at the i'th IN:

$$T_s^i = \frac{\eta\rho\left[\frac{l}{\lambda_c}+\frac{1}{h_f(V_f^i)}\right]+(T_f-T_a)}{h_n\left[\frac{l}{\lambda_c}+\frac{1}{h_f(V_f^i)}+\frac{1}{h_n}\right]}+T_a = \left(\frac{\eta\rho}{h_n}+T_a\right)+\frac{T_f-T_a-\frac{\eta\rho}{h_n}}{\frac{h_n l}{\lambda_c}+\frac{h_n}{h_f(V_f^i)}+1}. \tag{7}$$

The goal of the TCS is to minimize the temperature difference between the mirror surface and the ambient air, i.e., $T_s - T_a$ is as small as possible (ideally 0). Thus, the temperature difference of the mirror surface to the ambient air at the i'th IN can be presented as

$$\Delta T_s^i = T_s^i - T_a = \frac{\eta\rho}{h_n}+\frac{T_f-T_a-\frac{\eta\rho}{h_n}}{\frac{h_n l}{\lambda_c}+\frac{h_n}{h_f(V_f^i)}+1}, \quad i = 1,2,3\cdots N. \tag{8}$$

In a practical TCS, the air flow velocity of an IN (V_f^i) and its difference to the average air flow velocity of all the INs (ΔV_f^i) are measurable. Ideally, the fluctuation of velocities for all INs ΔV_f should be 0. Thus, the V_f can be treated as a measurable variable, and ΔV_f^i should be the deviation of the i'th measurement relative to the real value. In general, a Gaussian distribution (or normal distribution) is assumed to estimate the possible deviations of ΔV_f^i, i.e., the probability density of ΔV_f^i satisfies the Gaussian function $N\ (0, \sigma_V^2)$ (0, average value; σ_V, standard deviation), we can get that the probability density of V_f^i satisfies $N\ (V_f, \sigma_V^2)$, which can be expressed as

$$f(V_f) = \frac{1}{\sqrt{2\pi}\cdot\sigma_V}\exp\left[-\frac{(V_f-\overline{V_f})^2}{2\sigma_V^2}\right]. \tag{9}$$

A random set of V_f values can be generated by Eq. (9). The temperature value according to each V_f value can be calculated by Eq. (7) with given solar flux ρ and ambient air temperature T_a. The temperature differences between the mirror surface and the ambient air can be calculated by Eq. (8).

From the above analysis, a mathematic model can be built to describe the relation of the temperature homogeneity and the air flow velocity differences. At a certain moment, ρ and T_a can be measured or estimated; T_s and ΔT_s of the mirror surface at each IN can be calculated with the random set of V_f values generated by Eq. (9). So the average value $\overline{\Delta T_s}$ and the standard deviation $\sigma_{\Delta T}$ of the temperature differences can be estimated as

$$\overline{\Delta T_s} = \frac{1}{N}\sum_{i=1}^{N}\Delta T_s^i, \quad \sigma_{\Delta T} = \sqrt{\frac{\sum_{i=1}^{N}(\Delta T_s^i-\overline{\Delta T_s})^2}{N-1}}. \tag{10}$$

Applying the 3σ principle,[17] ΔT_s^i calculated by Eq. (8) should satisfy

$$[\overline{\Delta T_s}-3\sigma_{\Delta T}, \overline{\Delta T_s}+3\sigma_{\Delta T}] \subset [-\Delta T_0, +\Delta T_0], \tag{11}$$

where ΔT_0 is the specified maximum temperature difference between the mirror surface and the ambient air. $\subset$ is the mathematical contain symbol, which means the left range is contained completely within the right range. Equation (11) can be further simplified as

$$|\overline{\Delta T_s}| + 3\sigma_{\Delta T} \le |\Delta T_0|. \tag{12}$$

According to Eq. (12), we can calculate the critical standard deviation of the air flow velocity (σ_{V0}) by substituting random air flow velocities. The obtained σ_{V0} meets the temperature homogeneity requirement across the mirror surface. Therefore, the uniformity requirement for the air flow velocities can be defined by Eq. (13) in the design stage of a TCS:

$$\kappa \le \frac{1}{\zeta}\frac{\sigma_{V0}}{\overline{V_f}} \times 100\%, \tag{13}$$

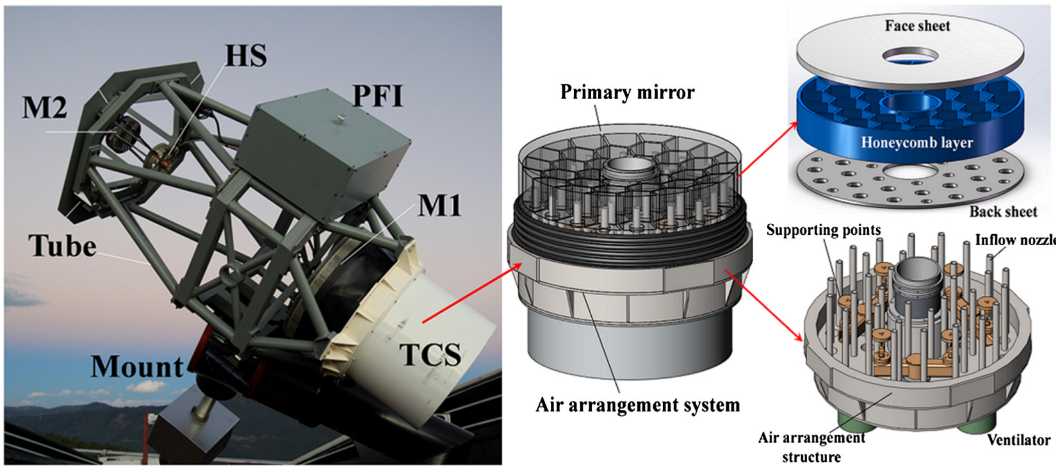
where ζ is the engineering coefficient representing the difference between the designed and the manufactured structures. In general, ζ ranges from 2 to 3 in different mechanic domains.

In practical application, (ρ, T_a) are time-varying, and the temperature homogeneity across the mirror surface with a given σ_V varies at different times. So, it should be calculated at different times to obtain a proper σ_V that always satisfies Eq. (13). For a certain ground-based solar telescope, some variables in Eq. (7) (such as η, l, d, D, H, λ_c, λ_a, and v) can be considered as constants over a small temperature range. The Prandtl number Pr is not strongly pressure and temperature dependent, and it can be treated as a constant number over a fairly wide range of pressure and temperature.[18] The solar flux ρ and the temperature of the ambient air T_a are related to the site and the time and can be estimated using the equations in Ref. 19 before the construction of a solar telescope. (Certainly, it is preferred to use the solar flux and the temperature of the ambient air that are recorded at the site.) Finally, the homogeneity requirement of the air flow velocities can be estimated according to the requirement of the temperature homogeneity across the mirror surface.

3 Experimental Validation of Engineering Coefficient Estimation on the POST

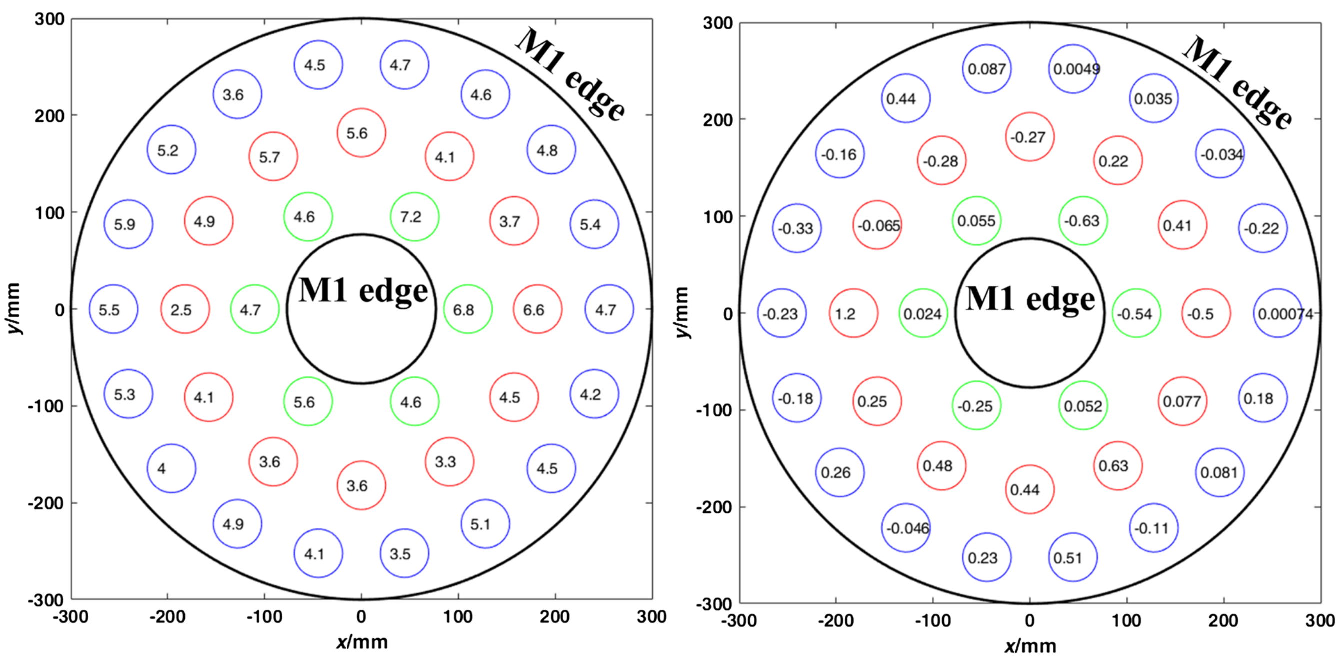
To validate the proposed mathematic model for temperature homogeneity control and to obtain a proper engineering coefficient ζ, we did several experiments on the POST, a 60-cm solar telescope.

The POST was built in Gaomeigu Observatory in Lijiang city, Yunnan province, China. As shown in Fig. 3, the POST utilizes single Gregorian optics design and open-tube truss



(a) (b)

Fig. 3 A picture of (a) the POST and (b) a sketch map of its TCS structure. M1, the primary mirror; M2, the secondary mirror; M3, the fold mirror; HS, the heat stop; PFI, the postfocus instruments; TCS, the thermal control system.



(a) (b)

Fig. 4 A random set of air flow velocities and its influence on the temperature of the mirror surface. (a) The air flow velocities of 36 INs. (b) The influence on the temperature of the mirror surface.

structure, which are similar to the CLST. The main parts of the TCS are a light-weighted primary mirror and an air arrangement system. The air arrangement system consists of an air arrangement structure, INs, and a ventilator. As a prototype of the CLST, the primary mirror of the POST is similar to the one of the CLST. Their optical and structural characteristics are the same, including the cavity size, the thickness of the face plate, the mirror material, the coating, and the F/number. d and H of the POST are 15 and 20 mm, respectively. There are 36 INs and a ventilator providing the air inflows at required velocity. According to our previous studies, 6 m/s is a well-balanced flow velocity, which requires a maximum temperature difference (between the inflow air and the ambient air) of −5.5°C; providing larger maximum temperature difference (−5.91°C) in our former experiment, the measured average air flow velocity of the 36 INs is about 4.73 m/s.

For the POST, the temperature homogeneity requirement across the mirror surface is within ±0.5°C, the same as for the CLST. According to the proposed mathematic model, we can estimate the temperature homogeneity control performance of its TCS by substituting different σ_V values. For easier understanding, we calculate the temperature differences at a fixed standard deviation (σ_V=1 m/s) at 12:00 local time ($\rho = 1200$ W/m^2 and $T_a = 14.1$°C). Figure 4 shows a random set of air flow velocities of 36 INs and the produced temperature differences on the mirror surface at each IN. The standard deviation of the air flow velocities is 1 m/s and the average velocity is 4.73 m/s. And the produced temperature differences on the mirror surface is 0.05°C in average ($\overline{\Delta T_s}$) with the standard deviation ($\sigma_{\Delta T}$) of 0.36°C. Substituting the values into Eq. (12), we get a value of 1.13°C, which is larger than the required ±0.5°C.

To obtain the critical requirement of σ_V for the POST, we input several sets of air flows with different standard deviations in velocities and estimate the temperature deviations during daytime. The σ_V ranges from 0.1 to 1.5 m/s with 0.1 m/s step length. Figure 5 shows the standard deviations of the temperature values on the mirror surface during daytime with air flows sets of different σ_V values. The maximum standard deviation of the temperature differences appears at noon, which is over 0.6°C with the σ_V of 1.5 m/s. The 3σ criterion of the temperature differences at noon with different σ_V values can be calculated by Eq. (12), as shown in Fig. 6. We make a curve fitting operation to acquire a more accurate estimation for the criteria requirement of σ_V (also shown in Fig. 6). The expression of the fitted curve is

$$|\overline{\Delta T}| + 3\sigma_{\Delta T} = 0.267\sigma_V^3 - 0.287\sigma_V^2 + 1.152\sigma_V - 0.015 \le \Delta T_0. \tag{14}$$

From Eq. (14), we know that the critical value of σ_V should be smaller than 0.473 m/s to satisfy the temperature homogeneity requirement of ±0.5°C.

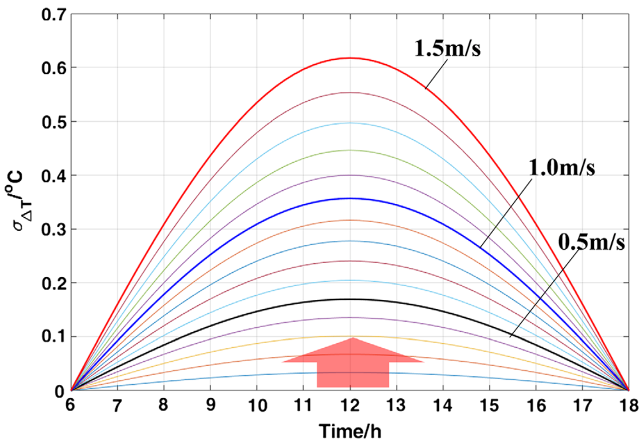


Fig. 5 The standard deviation values of the temperature differences during daytime with different σ_V values.

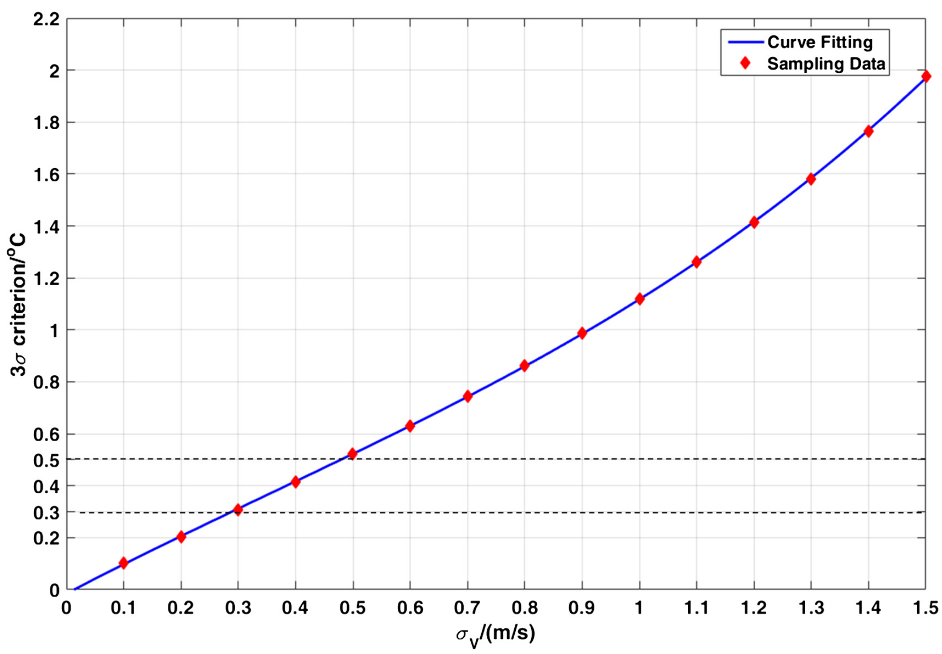


Fig. 6 The 3σ criterion of the temperature differences on the mirror surface with different σ_V values (POST).

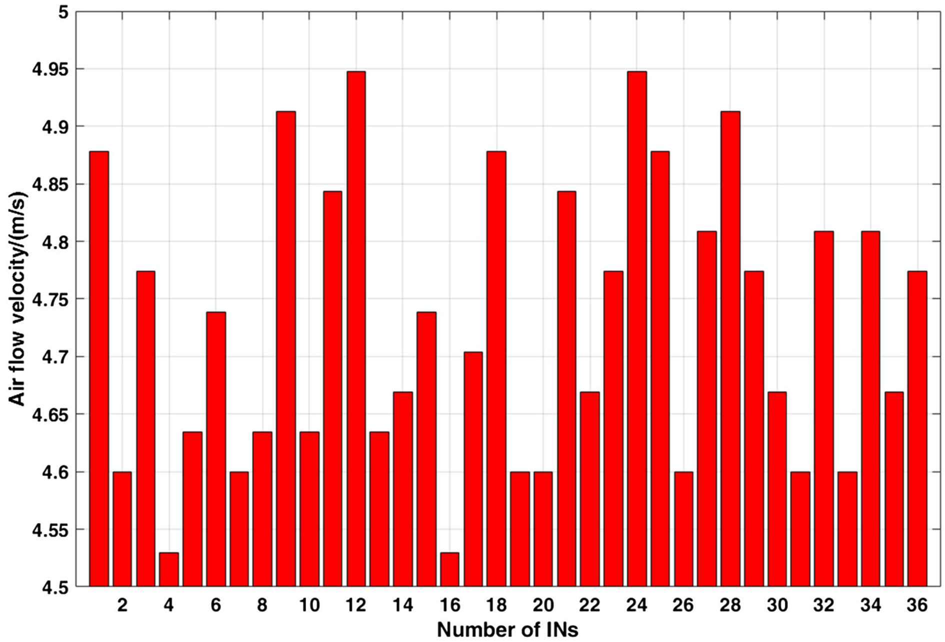


Fig. 7 Measurements of the air flow velocities of 36 INs.

According to this estimation, we carry out several experiments on the POST to measure the temperature homogeneity control performance of its TCS. Figure 7 shows the air flow velocities of 36 INs measured before the TCS is mounted to the POST. The air flow velocities range from 4.53 to 4.95 m/s, the average is 4.73 m/s, the standard deviation is about 0.123 m/s, and the uniformity of the air flow velocities (κ) is about 2.6%.

We measure the temperature homogeneity across the mirror surface of the POST at noon while it is operating. Three temperature sensors (FLUK, Pt100) with high accuracy (finer than ±0.05°C) are put on the mirror surface at three randomly selected positions. The temperature values monitored by the sensors and their differences are shown in Fig. 8.

From Fig. 9 we can see that, in over 98% of the time, the temperature differences are within −0.3°C to +0.3°C, which means the air flows with velocities shown in Fig. 7 meet the temperature homogeneity requirement of the POST (±0.5°C). The temperature differences at positions 1/2/3 are calculated from the differences between the temperature values at these positions and their average values, i.e., the summation of these three temperature differences at any time should be zero. That is why some kinds of anticorrelation of two temperature difference curves at positions 1 and 2 can be found from Fig. 8.

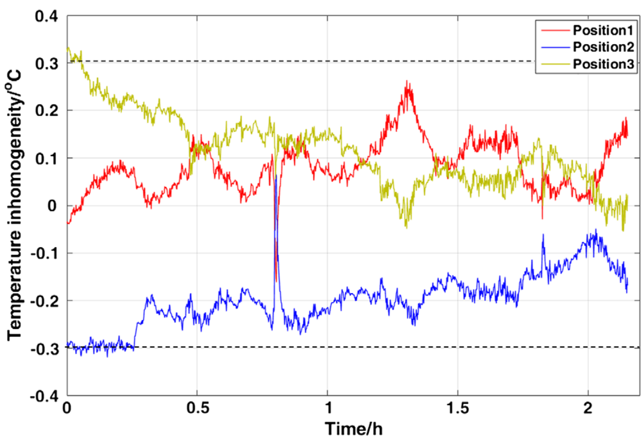


Fig. 8 The recorded temperature values on three positions of the mirror surface and their differences.

To estimate the practical engineering coefficient, we take ±0.3°C as the critical requirement of the temperature homogeneity and calculate the theoretical standard deviation of the air flow velocities, which is 0.298 m/s. Then, we obtain the estimated engineering coefficient, which is 2.423. It can be taken as a reference in estimating the critical requirement of σ_V by the CLST and by other ground-based solar telescopes with similar TCSs.

4 Performance Estimation of the CLST with the Proposed Model

The construction of a large ground-based solar telescope is time consuming and expensive. So it is essential to specify proper parameter values and estimate its performance in the design stage. Based on the studies above, we simulate several sets of air flow velocities with different uniformity to estimate the temperature homogeneity across the mirror surface of the CLST. This should make a good reference for the designing of other large ground-based solar telescopes.

The basic design of the TCS for the CLST can be found in our previous studies.[13,20,21] Here, we just illustrate the lightweighted honeycomb primary mirror and its air arrangement structure, as shown in Fig. 9. The honeycomb primary mirror and the air arrangement structure of the CLST and the POST are made of the same materials, and the optical $F/\#$ numbers of both are equal ($F/1.7$). Different from the POST, the TCS for the CLST includes three separate, identical cooling zones to adapt to the larger mirror. As shown in Fig. 9, 297 INs are inserted into the honeycomb sandwich layer, and three ventilators drive air through these INs to cool the backside of the face sheet.

Similarly, we estimate the temperature homogeneity control performance of the TCS by substituting different σ_V values. We also calculate the temperature differences across the mirror

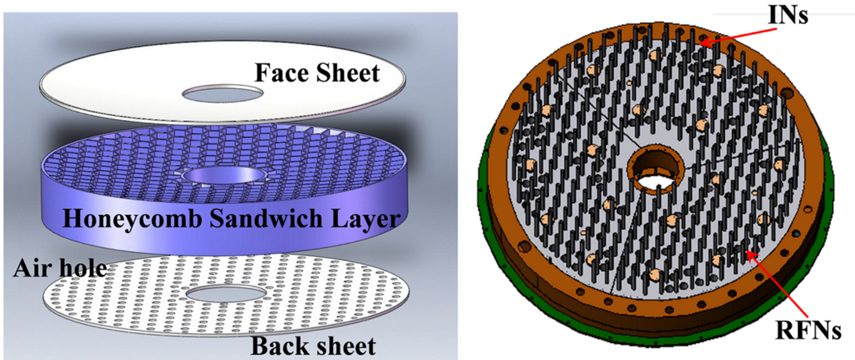


Fig. 9 The light-weighted honeycomb primary mirror and its air arrangement system (IN, inflow nozzle; RFN, return flow nozzle).

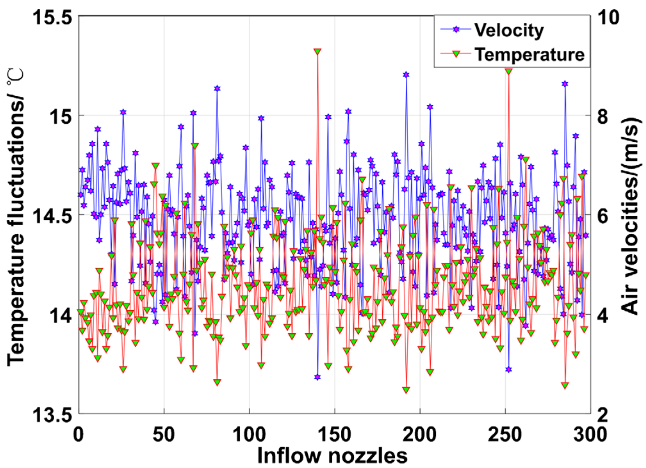


Fig. 10 The air flow velocities of 297 INs (blue line) and the produced temperature differences on the mirror surface (red line) ($\sigma_V = 1$ m/s, $\sigma_{\Delta T} = 0.24$°C).

surface at a fixed standard deviation (σ_V=1 m/s) at 12:00 local time ($\rho = 1200\ \mathrm{W/m^2}$ and $T_a = 14.1$°C), the same as we do on the POST. Figure 10 shows the random set of air flow velocities of 297 INs and the produced temperature differences on the mirror surface at each IN. The produced temperature differences on the mirror surface is 0.03°C in average ($\overline{\Delta T_s}$) with the standard deviation ($\sigma_{\Delta T}$) of 0.24°C. Without considering the engineering coefficient, we substitute these values into Eq. (12) and get a value of 0.75°C, which is larger than the required ±0.5°C.

Figure 11 shows the standard deviations of the temperature values on the mirror surface during daytime with air flows sets of σ_V ranging from 0.1 to 1.5 m/s, 0.1 m/s in step length. Similar to the POST, the maximum standard deviation of the temperature differences appears at noon, too. The maximum is over 0.4°C with the σ_V of 1.5 m/s. The maximum temperature differences of the POST and the CLST are not the same, because the averages of the air flow velocities for the POST and the CLST are not equal (POST, 4.73 m/s; CLST, 6.0 m/s[13]). Substitute the maximum average temperature difference and the standard deviation into Eq. (12), we get the relation of 3σ criterion and σ_V, as drawn in Fig. 12.

A curve fitting operation is also made to acquire a more accurate criteria requirement of σ_V. The expression of the fitted curve is

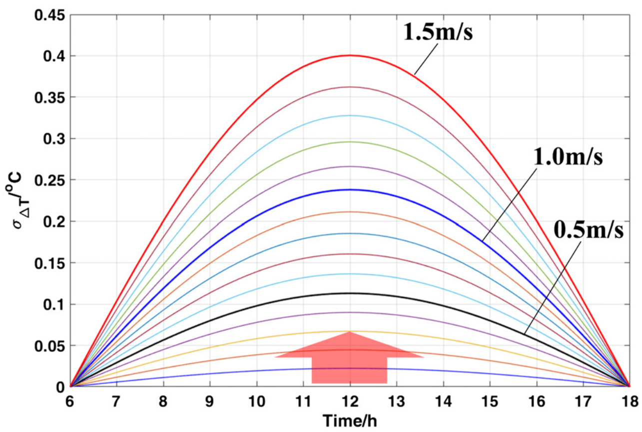


Fig. 11 The standard deviation values of the temperature differences during daytime with different σ_V values.

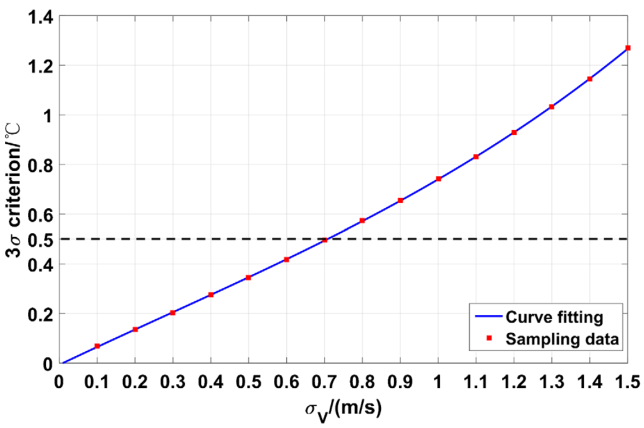


Fig. 12 The 3σ criterion of the temperature differences across the mirror surface with different σ_V values (CLST).

$$|\overline{\Delta T}| + 3\sigma_{\Delta T} = 0.122\sigma_V^3 - 0.101\sigma_V^2 + 0.726\sigma_V - 0.007 \le \Delta T_0. \tag{15}$$

To meet the temperature homogeneity requirement of ±0.5°C, the critical requirement of σ_V value should be smaller than 0.706 m/s. Applying the engineering coefficient of 2.423 obtained in Sec. 3, the critical requirement of σ_V should be smaller than 0.2914 m/s. The associated uniformity of the air flow velocities (κ) should be smaller than 4.86%. This should be a reference in designing the air arrangement system of a TCS for the primary mirror.

5 Conclusion and Discussion

In this paper, we propose a passive control method of the temperature homogeneity across the primary mirror surface of large ground-based solar telescopes. The core of the proposed method is to realize a uniform control of the air flow velocities of the INs. We derive the temperature homogeneity control model through analytical derivation. Then, we validated the model on the POST and estimated the engineering coefficient. We also apply the proposed model and estimation method to the CLST. We estimate the temperature homogeneity control parameter and simulate the performance of its TCS. In conclusion, to meet the temperature homogeneity requirement for the TCS of the CLST of ±0.5°C, the critical uniformity of the air flow velocities of 297 INs should be smaller than 4.86%. The proposed method is applicable to the designing of the TCSs for large ground-based solar telescopes, which ensures the temperature homogeneity across the mirror surface.

The proposed method needs further improvements in the future, such as considering the temperature fluctuations in the cavities of the sandwich layer, and the small differences in shape of the cavities, etc. Moreover, Eq. (3) has not been validated experimentally on the CLST whose H/d is 1.5.[22] These are the important endeavors of our future work.

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