CFD-Based Flow Analysis of Truss-Type Telescope Baffle Tube (Postprint)

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Abstract

The baffle tube affects the airflow above the primary mirror, which is detrimental to the heat exchange between the primary mirror surface and the surrounding air. Using the 50 cm telescope at Xinglong Station as an example, CFD software was employed to analyze the effects of two stray light suppression devices (baffle tube and independent baffle ring structure) on the airflow movement and temperature distribution in the primary mirror region. Concurrently, primary mirror seeing was calculated based on the temperature data. The analysis results indicate that the baffle tube leads to issues such as non-uniform temperature distribution, extensive turbulence effects, and asymmetric vortex flow. With the independent baffle ring structure, the primary mirror seeing was reduced by 74%. This demonstrates that the primary mirror baffle tube has significant drawbacks regarding primary mirror heat dissipation and air circulation. Integrating this analysis method with stray light analysis enables rational selection of stray light suppression schemes, which holds certain reference and application value for telescope design and modification.

Full Text

Analysis of Baffle Tube Turbulence in Truss Telescopes Based on CFD Software

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Abstract

The primary baffle tube influences airflow above the primary mirror, which is detrimental to heat exchange between the mirror surface and ambient air. Using the 50 cm telescope at Xinglong Observatory as a case study, Computational Fluid Dynamics (CFD) software was employed to analyze the effects of two stray light suppression devices—a baffle tube and an independent vane structure—on airflow dynamics and temperature distribution in the primary mirror region. Mirror seeing was calculated from the temperature data. The results demonstrate that the baffle tube causes non-uniform temperature distribution, extensive turbulence effects, and asymmetric vortex flow. In contrast, the independent vane structure reduces mirror seeing by 74%. This indicates that the primary baffle tube has significant disadvantages regarding mirror cooling and air circulation. Integrating this analytical method with stray light analysis enables rational selection of stray light suppression schemes, offering valuable reference and practical utility for telescope design and modification.

Keywords: Open truss telescope; CFD; Baffle; Turbulent model; Mirror seeing

1. Introduction

Stray light refers to non-imaging light that reaches the focal plane of an optical system. In telescope systems, stray light increases background noise at the image plane, reducing the signal-to-noise ratio of stellar images [?]. Among studies on stray light suppression for open truss telescopes both domestically and internationally, the most common approach involves using baffle tubes and vanes [?]. Installing a baffle tube at the central hole of the primary mirror effectively suppresses stray light from large incident angles. Vanes are typically mounted inside the primary mirror baffle tube to block internally scattered light. Compared with baffle tubes, vanes offer slightly weaker stray light suppression capability. However, as air passes through the baffle tube, flow disturbance occurs, affecting airflow movement above the primary mirror and causing image jitter, which degrades telescope imaging quality.

The Sloan Digital Sky Survey (SDSS) 2.5 m telescope [?] and the Las Cumbres Observatory Global Telescope Network (LCOGT) [?] both adopted independent vane structures to avoid airflow disturbance caused by baffle tubes. Computational Fluid Dynamics (CFD) software employs numerical computation and image display to analyze systems involving fluid flow and heat transfer. Although CFD methods have limitations such as boundary conditions that may not match reality and incomplete physical models, they can provide many results that cannot be measured experimentally, play an irreplaceable role in fluid mechanics analysis, and offer advantages for telescope design including low cost, the ability to simulate complex experimental environments, set measurement points at arbitrary locations, and provide data difficult to obtain experimentally. Through graphical user interfaces, airflow movement can be visualized intuitively, providing guidance for telescope design and modification without costly experiments [?].

2. CFD Simulation Model Description

2.1. Telescope Model Simplification The analysis of baffle tube turbulence only requires simulation of the primary mirror region, including the primary mirror and baffle tube. To reduce computational load, the telescope model was simplified. For the case with a baffle tube, since the vanes are inside the tube, the vanes themselves need not be considered. A rectangular fluid domain was established outside the simplified model to simulate the airflow region. If the fluid domain is too small, the flow around the baffle tube cannot be resolved; if too large, mesh count increases and computation time extends. After multiple simulations, a fluid domain size of 1.5 m × 1.5 m × 1.085 m was selected, with all boundaries except the bottom surface at a distance of 0.5 m from the telescope. The bottom boundary was set 0.01 m from the primary mirror' s bottom surface, as fluid below the primary mirror need not be considered.

The original model and CFD simplified models are shown in [Figure 4: see original paper]. The cube represents the fluid domain. Mesh generation was performed using ANSYS Workbench, which offers powerful pre-processing capabilities and adaptive tetrahedral meshes. Considering time cost and numerical dissipation, only the fluid domain and primary mirror were meshed.

2.2. Computational Methods and Parameter Settings The solution procedure for FLUENT software is illustrated in [Figure 3: see original paper]. In fluid mechanics, the Reynolds number (Re) characterizes flow regimes, distinguishing between laminar and turbulent flow. For this model, the characteristic length is the baffle tube diameter D = 0.14 m. At 0°C, air kinematic viscosity is $= 13.27\ \text{mm}^2/\text{s}$. According to meteorological data from Xinglong Observatory, the average wind speed on good observing nights is approximately V = 1 m/s, yielding Re = 10,550, indicating turbulent flow. When $V < 0.19$ m/s, $Re < 2{,}000$, placing the model in laminar flow. Since the telescope typically operates in turbulent conditions, only turbulent models were considered.

After multiple simulations, several common turbulence physical models showed little difference for telescope flow field analysis, and engineering application precision requirements are not particularly high. Therefore, the widely used improved RNG k- model [?] was selected, emphasizing wall temperature and buoyancy effects. The thermal model includes heat conduction and natural convection. Assuming an initial ambient temperature of 0°C, a velocity inlet was set at the left side of the fluid domain to simulate the dome slit, with the right side as the outlet. The primary mirror temperature was set to 5°C, wall conditions were no-slip, and other boundaries were set as free outflow boundaries.

3. Results Analysis

3.1. Fluid Dynamics Analysis Two working statuses were analyzed: (1) with baffle tube, and (2) with independent vanes. Data were extracted at 15,000 s after program initiation (two hours), when temperatures had stabilized and differences between the two cases were most pronounced. Three cross-sections were created for observation: wind direction as the view normal direction, and temperature scatter plot normal direction at 10 cm above the primary mirror surface.

[Figure 5: see original paper] shows temperature contours and scatter plots for both working statuses. In the scatter plots, white points represent primary mirror surface temperatures. For status 1 (with baffle tube), temperature differences exist within the baffle tube, causing non-uniform mirror cooling with slower cooling on the leeward side. This creates temperature differences in the air above the mirror surface. Since this occurs in the telescope' s optical path, temperature differences induce turbulence that degrades resolution. For status 2 (with vanes), the mirror cools uniformly with smaller surface temperature gradients. No temperature difference exists at 10 cm above the mirror surface, and the mirror surface temperature is lower than in status 1.

[Figure 6: see original paper] presents turbulence intensity contours (black circle indicates mirror profile). The 3D turbulence contours show that status 1 has a maximum turbulence intensity of 21.63% in a small region at the upper middle portion outside the baffle tube. The top view reveals asymmetric vortex flow behind the baffle tube. For status 2, the maximum turbulence intensity is 31.63%, distributed along the vane support rods. However, the area with significant impact is small, comprising only yellow and green regions. The most affected area is the blue region to the right of the vanes, just 4 mm from the support rods, where turbulence intensity is only 16.33%. Since turbulence intensity I is inversely proportional to characteristic length D, the impact is limited.

When fluid flows past a cylinder, a Kármán vortex street forms [?], creating alternating vortices that cause different instantaneous velocities on either side of the bluff body. [Figure 7: see original paper] shows velocity contours. For status 1, wind speed is symmetrically distributed before the baffle tube but forms an asymmetric vortex pair behind it, with large differences in speed before and after the tube. The maximum speed is 1.42 m/s. For status 2, the distribution remains symmetric before the vanes with no vortex shedding, and the overall velocity distribution is more uniform with a maximum speed of 1.37 m/s. Vane thickness has minimal impact on airflow.

[Table:1] summarizes the ranges of temperature, turbulence intensity, and velocity for both working statuses.

3.2. Mirror Seeing Calculation When the primary mirror has a temperature difference with its surroundings, the turbulent boundary layer above the mirror surface degrades image quality. Researchers have conducted extensive studies on mirror seeing [?]. By combining the temperature structure function in the turbulent inertial subrange with the Kolmogorov expression for atmospheric refractive index and neglecting humidity effects, the full width at half maximum (FWHM) of stellar images can be expressed as:

$$\theta = 8.418 \frac{\lambda^{-1/5}}{T^2} \int_0^\infty C_T^2(z)\, dz$$

where λ is wavelength (m), T is temperature (K), and C_T^2 is the temperature structure coefficient. Assuming zenith angle $\gamma = 0°$, $\lambda = 500$ nm, and Xinglong Observatory altitude of 960 m (90,125 Pa, or 901 mbar), the equation simplifies to:

$$\theta = 0.15'' \int_0^\infty C_T^2(z)\, dz$$

Temperature monitoring points at different heights above the mirror surface were set in the CFD software to calculate mirror seeing. [Figure 8: see original paper] shows scatter plots and fitted curves for both statuses. Overall, C_T^2 gradually increases from the mirror surface to 10 cm, then decreases with height. The temperature difference increases with height, so C_T^2 decreases accordingly. At 10 cm above the mirror, there is essentially no temperature difference. The final calculated mirror seeing is 0.23” for status 1 and 0.04” for status 2—a 74% reduction. Under these conditions, both values are small enough to have no substantive impact on telescope imaging.

3.3. Mirror Seeing Calculation Method Validation Semi-empirical formulas for mirror seeing have been developed from studies of the 25 cm telescope [?], 62 cm mirror [?], and other telescopes [?]. For ventilated conditions:

$$\theta = 0.18 \frac{g^{1/3}}{V^{1/6} D^{1/3}} \Delta T^{1.3}$$

where g is gravitational acceleration, D is primary mirror diameter, V is wind speed at mirror surface, and ΔT is temperature difference between mirror surface and ambient air. Since the 50 cm telescope has similar aperture, this formula was applied with reference temperature $T = 0°C$. [Table:2] compares mirror seeing calculated by CFD with that from the semi-empirical formula under different temperature differences and wind speeds. The differences are small, indicating that mirror seeing is primarily sensitive to temperature variations, consistent with previous research [?].

4. Summary and Outlook

This study established a CFD simulation model for the 50 cm telescope at Xinglong Observatory to analyze airflow conditions in the primary mirror region for both baffle tube and independent vane structures. The analysis provides temperature, velocity, and turbulence distribution maps that are difficult to obtain experimentally. Mirror seeing was calculated from temperature data. The results demonstrate that independent vane structures are superior to traditional baffle tubes in terms of air circulation and mirror cooling.

Since the CFD model is based on simplified and assumed physical models, actual turbulence and atmospheric instability cannot be fully described mathematically. The analysis can qualitatively show that independent vane structures outperform baffle tubes for mirror seeing control, though quantitative accuracy requires comparison with measured data. Experimental costs for 50 cm telescopes are high, and measuring velocity and turbulence distributions is challenging. The simulation results are valuable for analyzing turbulence characteristics of different structures to guide rational selection of stray light suppression devices.

Compared with baffle tubes, independent vane structures offer the following advantages: (1) more uniform mirror cooling and smaller temperature gradients throughout the model; (2) 6.51% lower turbulence intensity in significantly affected regions; (3) no vortex shedding; (4) minimal impact from vane thickness on airflow; (5) more uniform velocity distribution; and (6) 74% reduction in mirror seeing. Integrating these results with stray light analysis enables optimal selection of suppression devices, providing valuable guidance for telescope and dome design. Future research will compare CFD-simulated mirror cooling processes with actual measurements to validate the model and extend this method to analyze airflow and seeing for any telescope.

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