Mechanical design of the heater used in near infrared filter

Jun Ma
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ABSTRACT

MECHANICAL DESIGN OF THE HEATER USED IN NEAR INFRARED FILTER

By
Jun Ma

This thesis presents a design and analytical process in the application of the heater used in a near infrared filter working in Big Bear Solar Observatory, CA. The objective of the project is to achieve the physics parameters for the filter, which will be used in the observation of the solar activity.

The most important part of this design is to keep a relatively fixed temperature inside the oven-like heater. The reason is that optical properties of calcite (kind of filter in telescope) are pretty sensitive to a tiny disturbance on inside temperature. This was the biggest issue in this design. In cooperation with Dr. Jingshan Wang, former Ph.D. candidate in Physics at NJIT, several ways were attempted to achieve the acceptable temperature disturbance, and accordingly, a decision was reached to leverage the excellent heat insulating property of industry PVC material to make the plan work. The important role of PVC insulation discs in the functionalities of the heater will be presented.

The second most important thing is the mechanical structure. The design should guaranty good heat conductivity for the container holding calcite so that it’s respectively easy to achieve a uniform temperature field. Sometimes, the trade-off between mechanical structure and physics capacity turned out to be a quite difficult regression process. Finally, even the position of a bolt will cause much consideration due to the heat dissipation. Also, operation of this equipment must be taken into account, because this will affect the design of the mechanical structure.
MECHANICAL DESIGN OF THE HEATER
USED IN NEAR INFRARED FILTER

by

Jun Ma

A Thesis
Submitted to the faculty of
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in Fulfillment of the Requirements for the Degree of
Master of Science in Mechanical Engineering

Department of Mechanical Engineering

August 2001
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To my Parents
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CHAPTER 1
INTRODUCTION

1.1 Astronomy Background

Temperature is one of the most important factors in Astronomy instrumentation. Therefore, one can always find the tracks of temperature in every observation checklist. One of the most prominent negative effects of the temperature applying on observation system is focus offset. From an experimental result, the telescope focus changes by ± 42 microns per °C. Although the meaning of “changes” here has some kind of special context, the negative role of temperature in telescope systems is obvious. For that reason, telescope systems always have some kind of adaptive adjusting system to remedy the offset of system, automatically or manually. However the adjustment is always a time-consuming process.

1.2 General Introduction of the Project

In the machine design project for the mission in BBSO, the thermal factor is acting on the calcite’s birefringent index. More detail on the topic of optical principle for calcite can be found in Jing-Shan Wang’s paper [2].

“The birefringent index of calcite, $\mu = n_e - n_o$, is a function of wavelength $\lambda$ and temperature $T$. Therefore, when measuring $\mu$ the temperature of the calcite must be stabilized with a controller (of accuracy ± 0.1°C at least). A sample calcite plate with its thickness, $d_0 = 10498.0 \pm 3.0 \mu m$ at $T_0 = 69.0 \degree F (21.56 \degree C)$ was used
in this measurement. The thermal expansion coefficient along the direction perpendicular to axis of calcite is $\beta = -3.7 \times 10^{-6}/K$.

Because these calcites will be applied in solar observation system, their birefringent index must be known; at least their magnitude should be researched.

Considering the octagon shape of calcites, groups of calcite are enclosed in a tube with a square hole. An electrical wired heater is wrapped outside of this oven-like tube acting as heat resource. It’s better if this wired heater could be controlled precisely, because this is the only factor that can be adjusted by researcher. The general picture can be achieved from Figure 1.1, although there are several important parts concealed.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{heating_system.png}
\caption{Global view of heating system}
\end{figure}

There are at least four probes will be put downward on the top of upper cover, so that user is able to know the temperature inside of the tube. These probes are temperature sensors, and they can be controlled adaptively and automatically in experiment. Tom Spirock, PhD candidate in Electrical Engineering at NJIT, designed

\footnote{Tom Spirock, PhD candidate in Electrical Engineering at NJIT. He is focusing on electrical circuit design in this project.}
the controlling circuit and selected an electric heater and probe. At both ends of the tube, two windows with O-ring seals are placed to keep a stable temperature and a clean environment. Windows are double-layered. The light beam will go through window's glasses, calcites, and window glasses again.

The whole system is mounted on a high stiffness frame, which can slide on a bench. The two supporting frames are made of aluminum. Because of their perfect heat conductivity, two insulators were plugged in to frame, which is an effective way to keep the temperature inside the tube. These parts can be found in Figure 1.1 in details.
CHAPTER 2
HEATER DESIGN

2.1 The Temperature Issue in the field of Telescope Design

Practically in the fields of astronomy observation, keeping a relatively stable temperature field for telescope and measuring temperature field are very important work. In most cases, they are also time-consuming and labor intensive tasks, because the heat transfer is an intrinsically slow physical process. To directly measure the performance of mirror temperature control systems, one requires sensors with relative accuracies of 100 m °C peak-valley spaced at 0.03 m intervals. In practice, because of the spatial uniformity of the thermal environment, less frequent spatial sampling is necessary. An analytic result shows that thermal properties appear to be well resolved by sensors separated by 0.2 m or more. However at the same time, hundreds of sensors may be applied. Here are several cases successfully used in other telescope system.

One approach uses thermocouples. Thermocouples produce the voltages, which are naturally stable and proportional to the temperature difference between the thermocouple and the reference junction. However the negative point of this method is that it’s difficult to amplify signals. Since the signal must be measured to the microvolt level to achieve the desired temperature resolution, the requirement of lower external electronic disturbance might be strict.

The other approach uses silicon integrated circuit sensors. It’s easy and reliable to multiplex signals from hundreds of sensors. The weak point is the complexity of using such a numerous sensors at the same time and calibrate them. However, for the
project in BBSO, it's not a big problem, because the small tube used in the project is not really a big telescope house. At most, only six sensors (RDT-850) are placed inside of the tube, which is adequate to get the desired accuracy.

2.2 The Mechanism for this Design

The following is the flow chart for mechanical design.

![Flow chart of design](image)

**Figure 2.1** Flow chart of design

Mechanical structure design process will be always interacting with thermal design in this project. Sometimes, mechanical structure needs to be redesigned to solve the thermal issue.
CHAPTER 3
MECHANICAL STRUCTURE DESIGN

3.1 Tube Design

This tube is the most important part in the whole design. Because the calcites are put directly on its inner surface, high-quality inner surface and high-precision related features, as parallelism, position, etc., are required in manufacturing. Considering the operation issue, the original design was to place calcites on a cage (Figure 3.1.1), and then, put cage inside tube.

![Figure 3.1: Assumption - Using cage modular to hold calcite](image)

However, the complexity to manufacture it stops this design approach. Another simpler approach can be used to complete it. The shortcoming to put calcites directly on the inner surface of tube is that it takes the risk to damage calcites in practical operation. Although putting several holders inside tube to clamp calcites is pretty effective, operator must be very careful to take out/put in calcites.
3.2 Supporting Frame

3.2.1 Mechanical Structure

Considering the frame will support all parts in this testing system, stiffness of frame should be guaranteed.

Figure 3.2 Up-front view of heating system & calcites’ position

Figure 3.3 Mounting structure
3.2.2 Thermal Factor in Mechanical Design

The big issue here is the heat lost from this aluminum frame. So that between mounts and tube, an insulator made of PVC (plastic material) is plugged in. In Chapter 4., the effect of this insulator will be researched in details.

3.3 Window for Observation and Operation

At both ends of the tube, heat radiation and convection in air turn out to be the prominent heat lost introducer. Double-layered windows were used to prevent energy lost. In the practical application, these two windows can be removed, so that calcites can be put into tube. Although tube is made up of two parts, it can't be opened in the process of experiment, because it will be wrapped by an electrical wired heater like a sandwich.
CHAPTER 4
THERMAL DESIGN & ANALYSIS

In this chapter, thermal consideration will be examined in details. First of all, a mathematical model for heater design has been built. Considering the mechanical structure is almost axi-symmetric in geometry shape, in most cases, only the cross sections of parts and contact interfaces were considered. Because the tube is enclosed with two windows at both ends, heat convection happens only inside of tube, which will not be a big concern.

In this design, not all parts deserve to be researched in thermal aspect. Heat conductive on the cross section of tube, contact interface between tube and insulator. The radiation from mounts and frames are also taken into account. For calcites, the temperature field around it will be researched in details, so that its working performance can be understood.

4.1 Mathematical model for Heat Transfer Problem

The general form of heat transfer equation came from the talented French mathematician, Joseph Fourier [5]. It takes the following general form:

\[ q = -k \cdot \text{grad}T - \tau, \frac{\partial q}{\partial t} \]  \hspace{1cm} (4.1.1)

Function (4.1.1) is a "corrected" Fourier Law, which means the second term on the right side of equation (4.1.1) represents heat inertia. If there is no inertia term in function, one assumption can be made. Fourier Law’s assumption is: heat flux propagates in a medium at infinite speed. However, for the high-intensity and/or unsteady heat dynamic process,
dynamic process, heat flux propagation speed must be taken into account. Therefore, it's reasonable to add an inertia term into original Fourier Law. $\tau_r = \text{const}$ is the relaxation time of heat stresses.

Considering the relationship between heat flux and temperature,

$$ q = c\rho \cdot \text{grad}T $$

so that

$$ c\rho \left( \frac{\partial T}{\partial t} + \tau_r \frac{\partial^2 T}{\partial t^2} \right) = \nabla (k \cdot \text{grad}T) + f + \tau_r \frac{\partial f}{\partial t} \quad (4.1.3) $$

where

$c$ — heat capacity, $\rho$ — density, $k$ — thermal conductivity

This is the controlling equation in heat transfer process for heat conductivity.

In order to solve controlling equation, appropriate boundary condition should be attached to form a close P.D.E problem. At least, two groups of boundary condition can be developed: Dirichlet Condition, Neumann Condition.

Dirichlet Condition:

$$ T(x, y, z, t) = g(x, y, x, t) $$

where: $(x, y, z, t) \in \Gamma$ \hspace{1cm} (4.1.4)

$$ \Gamma = \{(x, y, z, t) | (x, y, z) \in \partial \Omega, 0 < t < t_{\text{max}}\} $$

Neumann Condition:

$$ k \frac{\partial T}{\partial n} = q(x, y, z, t) \quad (4.1.5) $$

where: $(x, y, z, t) \in \Gamma$
However, according to different situations, boundary conditions might vary in their forms. Several cases will be researched below, as: on the contact interface, on the cross-section.

Despite of heat conductive, the **thermal radiation** is another primary energy lost in this design, especially from the two windows at both ends of tube, and from the surfaces of two mounts on the frame.

From quanta mechanics theorem, the **integral density** \( (E) \) for the flux of energy of surface radiation passing through a unit surface area has the following relationship with quanta frequency \( (\nu) \):

\[
E_\nu = \frac{dE}{d\nu}
\]  

(4.1.6)

\( E_\nu \) is named **spectral (monochromatic) density**, which represents the energy quantity for a unit frequency interval. For solids, because they are opaque for heat rays unless very thin, internal radiation process can be neglected, and the surface radiation is the only term left. For “black body”, **Plank Law** give us the following form:

\[
E_\nu = 2\pi \frac{h\nu^3}{c^2} \frac{1}{\exp(m\nu/T) - 1}
\]  

(4.1.7)

so,

\[
E = \int_0^\infty E_\nu d\nu = \sigma T^4
\]  

(4.1.8)

where, \( \sigma \) is called **Stefan-Boltzmann constant**. And equation (4.2.8) is named **Stefan-Boltzmann Law**. A recommended value for \( \sigma \) comes from CODATA (Committee on Data for Science and Technology) is:

\[
\sigma = 5.670400 \times 10^{-8} \, J \cdot m^{-2} \cdot K^{-4}
\]
For non-black body, 

$$E = \int_0^\infty E_r \, d\nu = \varepsilon \sigma T^4$$  \hspace{1cm} (4.1.9)

$\varepsilon$ is called fraction of radiation ("blackness") of object, which is a value less than 1.

Once the radiation term has been achieved, the boundary condition could be written as:

$$k \frac{\partial T}{\partial n} + \alpha (T - T_e) + \varepsilon \sigma T^4 = 0$$  \hspace{1cm} (4.1.10)

$$(x, y, z) \in \partial \Omega$$

For now, two sets of equations have been achieved. One is the controlling equation for thermal conductivity process and its boundary condition; the other is the controlling equation for thermal radiation process and its corresponding boundary condition. In the rest of this chapter, several special heat transfer cases will be researched respectively and numerical results will be presented leveraging the powerful engineering software package, ANSYS® from ANSYS, Inc.

4.2 Analysis of Heat Transfer on Cross-Section

4.2.1 Transient Analysis - Dynamics of Heat Transfer on Cross-section

One of the most interesting concerns in this design is about the operation time. How long will it take from the initial temperature to a stable temperature field inside tube? The electric heater used in experiment is flexible silicone rubber fiberglass insulated heater, which can be adaptively controlled from outside of tube. Its heating energy density is 2.5 W/in$^2$ (i.e. 3875 W/m$^2$).
Table 4.1 Physical properties of tube

<table>
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<tr>
<th>Material</th>
<th>Conductivity (W/m·°C)</th>
<th>Density (kg/m³)</th>
<th>Specific Heat (J/kg·°C)</th>
</tr>
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<tbody>
<tr>
<td>Aluminum-5052</td>
<td>144.0</td>
<td>2.69E+3</td>
<td>963.0</td>
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Figure 4.1 Heat transfer on cross section

4.2.2 FEA Simulation for Dynamic Temperature Field

With ANSYS 5.5, a color-coded contour can be achieved by solving the P.D.E of heat transfer. Figure 4.2.2 shows the temperature distribution at time 420s. It’s pretty useful to know the time range to achieve this heat status. From this simulation, it takes about 7 minutes to achieve desired temperature at the inner edges. However, practically, it will take a little longer to do so, because of the adaptive adjusting process around the desired temperature.
Figure 4.2 Temperature distributions on the cross section of tube

4.3 Heat Transfer through Multi-layered Wall

The mathematical model for multi-layered wall takes the following form:

\[ T_n - T_i = q \times \left( \sum \frac{t_i}{k_i \times A_i} \right) \]  \hspace{1cm} (4.3.1)

where, \( t_i \), \( k_i \), \( A_i \) are thickness, conductivity, and cross-section area of the layer \( i \), consecutively. From this formula, around the two windows at both ends, it's easy to derive the heat lost for heater design:

\[ q_{\text{multilayer}} = \left( T_n - T_i \right) \left/ \left( \sum \frac{t_i}{k_i \times A_i} \right) \right. \]  \hspace{1cm} (4.3.2)
Actually, the two windows are almost the only approach for heat energy to escape (the other outer surfaces are covered by some soft heat insulator). Therefore, this portion holds a significant part of heat lost in the heater design.
5.1 Machinery Design Experience

To achieve the desired performance for the heater, most part of the time was spent to design its mechanical structure and deal manufacturing issue. For instances, the cube hole centered in the cylinder is the most headache part. Because it's difficult to drill it using the usual tools, it's separated into two parts, the upper and the lower. The centered cube notch was manufactured in high accuracy to guarantee the parallelism for the calcite and the optical axis of the whole system.

The other example appeared in the design of the windows. The diameter of window is very small, which depends on the diameter of calcite, therefore, it's impossible to use hands to operate calcites. That’s the reason why cage-like frame might be used (Figure 3.1.1), which could be easier for operation. However, the structure of this cage is so complicated that it will introduce prominent manufacturing errors. Finally, instead of using cage, an inside holder was used to operate calcites. It can be used to push calcites smoothly in/out tube.

5.2 Heater Performance

The heat performance is always the first concern in this design. Several kinds of insulation methods were applied in this tube. The two windows are also one of the primary methods to achieve an acceptable uniform temperature field. From the optics experiment results, the heater did an acceptable job in the whole system. Here are two
pictures from JingShan Wang's spectrograph test, which show the transmission image of each pair of calcite and simulated pass-band of the near-IR birefringent Filter.

(a)~(d): transmission images of calcite;

(f)~(i): normalized profiles of the transmission images,

(e): simulated pass-band of the filter (product of image (a), (b), (c) and (d));

(j): normalized simulation profile of the pass-band of filter.

Figure 5.1 Spectrograph testing results of the calcites
CHAPTER 6
FUTURE RESEARCH ISSUES

6.1 Possible Improvements in Heater

This heater is working in BBSO now. Several weak points were figured out in practices. One is operating calcites is still a tough job. Sometimes, the holders inside the tube are stuck because of holders' heat expansibility. Now the holder is made of PVC, other materials can be considered to substitute PVC. The other point is the window. Window is designed without considering of operating flexibility, which induces some trouble to handle calcites timely in experiment. It can be improved if the diameter of the window is enlarged. However the mounts should be redesigned at the same time.

6.2 Future Research About Heat Transfer

In this thesis, only cross-section heat transfer, multi-layer heat transfer and heat radiation are considered. The other approaches of heat transfer in this design include: heat transfer on contacting faces, heat lost from bolts & little hole were not taken into account. Although their effects are not so prominent in the design, it will be helpful to give them some consideration in the future.
APPENDIX A

MECHANICAL DRAWINGS

This is the assembly view of all the parts of the heating equipment.

Figure A-1 Assembly view of heating equipment
This is mechanical drawing of the lower part of the tube.

**Figure A-2** Lower part of the tube
This is mechanical drawing of the top part of the tube.

Figure A-3 Upper part of the tube without sensors
This is mechanical drawing of the top part of the tube with sensor holes.

Figure A-4 Upper Part of tube with holes for sensors
This is mechanical drawing of the retard plate.

Figure A-5  Insulate Plate I
This is a mechanical drawing of the supporting plate.

**Figure A-6** Insulate Plate II
This is mechanical drawing of the supporting frame.

Figure A-7  Mounting Frame
This is mechanical drawing of the windows.

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<thead>
<tr>
<th>NAME</th>
<th>MATERIAL</th>
<th>NUM</th>
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<tbody>
<tr>
<td>WINDOW</td>
<td>ALUMINUM</td>
<td>2</td>
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</table>

Figure A-8  Windows at both ends of the tube
APPENDIX B

PICTURES OF THE HEATER

This is the final equipment with all parts and utilities of the heater.

Figure B-1  Assembled Equipment
REFERENCES


