Implementation of Multi-layer Insulation for The Small Aperature Telescope

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INTRODUCTION

The need for MLI This project aims to find theorized gravitational waves in the CMB by building a small aperture telescope or SAT for short. The detectors in the telescope are transition edge sensors or TES for short which need to operate at their transition temperature which is on the order of magnitude of millikelvin. To achieve this temperature, we need to create thermal shielding in stages in the SAT which takes the form of layers of aluminum stages and multi-layer insulation aka MLI. To validate that our system can reach these cool temperatures MLI had to be designed, made, cut, and installed on the system to protect the lower stages from the radiative load from the hotter stages.

Describing specific project While the broad goal of this project is focused on the detection of the B modes and the tensor-to-scalar ratio defined as r; the project undertaken at Princeton for the summer is to validate that the SAT we are constructing is capable of achieving 4 K temperature inside the cryostat in order to continue to the next step of receiving a DR, dilution refrigerator to bring the temperature of the inner stages down to millikelvin. The question is then how we will achieve this temperature. This has been done numerous times in other projects such as ABS, Atacama B-mode Search, the goal of this summer will be to achieve this 4K while being expeditious, low cost, and making the best insulation possible. Our team is working with a number of collaborators at other schools making other SATs and even parts that will be included in our SAT such as the optics tube and the HWP, half wave plate. Our project has to stay on schedule so that we can be of service if these systems need to be tested in our cryostat. The project is trying to improve the insulation of the other SATs. While they ordered from a professional company, Ruag, our MLI has the possibility of performing better during the cooldown if we hand cut and try to optimize the MLI.

FIG. 1. TSAT outer vacuum chamber displayed in lab with the port on the top left of the image being for the pulse tube that was used in the experiment for this paper

HEAT TRANSFER FOR MLI

describe the math behind it In this grand project we focused on the insulation component of the system specifically implementing the MLI layers in a way to minimize the amount of heat that got to each layer. The MLI blankets are necessary because (math behind the radiant heat). This is an enormous amount of heat considering that we have a 40K stage and a 4K stage and even colder. The blankets work to reflect a large amount of this incident radiation which can be characterized by their extremely low emissivity. Although other SATs employed a professional manufacturer to make the blankets our project dud not because of the price and that their blankets could be improved. Working off of the CAD plans for the blankets of the other SATs we could gauge roughly what shapes needed to be made. Some of these shapes were extremely large and it was necessary for a large flat surface to be made in order to cut the blankets. We then extended a table with two pieces of 4x8ft plywood with supporting legs to make this surface. Then two rods were added so that the MLI materials would be able to be rolled out along the table. One rod for the aluminized mylar and the other for the netting. The netting acts like a spacer in between the aluminized mylar to add loft to the MLI.

View Factor

In the thermal calculations it is important to understand the view which is described as F in the equations used in this paper and more generally. The view factor is defined as the fraction of the total radiation that leaves a surface that comes into contact with another. This implies the summation rule which is that the sum of all of the view factors from a specific surface needs to equal 1. This is convenient because with two spheres that are concentric and one is enclosed, the view factor from the enclosed sphere to the outer sphere is 1. This is true by investigation or examining the problem because the radiant energy from the enclosed sphere can reach no surface but that of the outer sphere. Below is a diagram representing the derivation of the view factor and the general equation.

$$F_{21} = \frac{1}{A_2}\int_{A_1}\int_{A_2} \frac{\cos\phi_1 \cos\phi_2}{\pi r^2} dA_1 dA_2 \qquad (10)$$

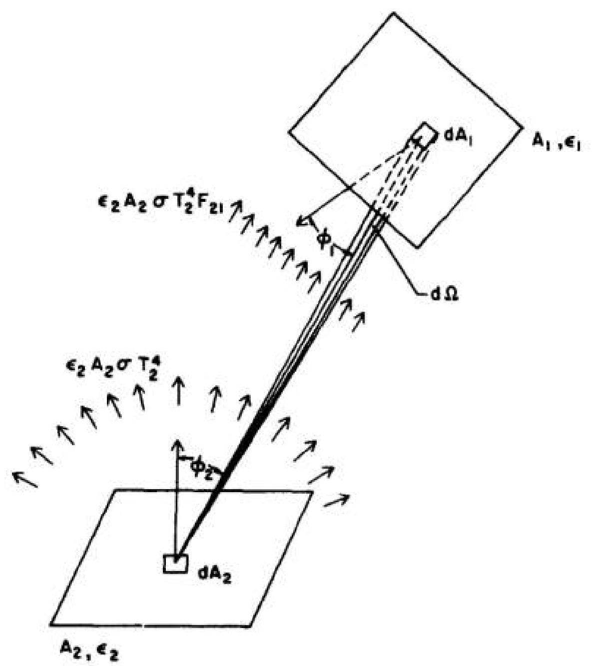

FIG. 2. Definition and diagram representation of view factor for two greybodies

For the experiment the shells were approximated as enclosed cylinders which made the calculations for the view factor much more simple. The view factor for the inner cylinder onto the outer cylinder was 1 because of summation and with the rule of reciprocity:

$$A_i F_{ij} = A_j F_{ji}$$

Only the surface areas of each cylinder had to be measured in order to obtain the view factor for the larger cylinder onto the smaller one.

This equation describes the heat transfer between two enclosed cylinders that act like grey bodies:

$$q_{1-2} = \frac{\sigma A_1 (T_2^4 - T_1^4)}{\frac{1}{\epsilon_1} + \frac{A_1}{A_2}(\frac{1}{\epsilon_2} - 1)} F_{12}$$

sigma is the Stefan Boltzmann which is used to describe the power of blackbody radiation. The T are the respective temperatures in Kelvin for the outer cylinder at room temperature and the inner stage with the subscript denoting that 2 is the outer cylinder and 1 is the inner. The A is the respective surface area of each cylinder, in particular the outer surface area of the inner cylinder and the inner surface of the outer cylinder. For our application of MLI each layer can be described as a radiation shield which increases the quantities being added in the denominator.

$$q_{c-h} = \frac{\sigma A_c (T_h^4 - T_c^4)}{\frac{1}{\epsilon_m} + \frac{A_c}{A_h}(\frac{1}{\epsilon_{Al}} - 1) + 29\frac{1}{\epsilon_m} + \frac{1}{\epsilon_{Al}}} F_{12}$$

How effective emissivity is being defined:

$$\epsilon_{eff} = \frac{q_{total}}{\sigma A_1 (T_2^4 - T_1^4)}$$

The loft is the density of the layers which is important so that the heat does not transfer between the layers. In the border condition where there is no loft or spacer and the aluminized mylar is touching each layer, the heat could transfer between the layer through conduction which would heat up the layers together. In the other border case where there are poles of 6 cm separating the blankets then the conduction term would completely be eliminated but using 30 layers would make the blankets 1.8m thick which is much larger than the space inside of our cryostat. Finding the middle ground where the blankets are lofty enough not that conductive heat transfer is not a problem while still fitting with the design requirements.

PRODUCTION

The blankets were made by lying down sheets of aluminized mylar while lying a sheet of netting down in between each layer. This was done until there were 7-10 layers of aluminized mylar depending on the specific section being completed. Many times dimensions were scaled up in order to accommodate for the thickness of the MLI blankets underneath it.

tools used to cut Different tools were used to cut the blanket as shown in FIG. 3. The razor blade is best used with a long straight edge such as a ruler or a level for great straight lines while the scissors are a lot better for cuts that were curved such as cricles or arcs.

In order to lay out the layers a table was necessary. We built one in lab out of an existing table, 2 4x8 pieces of half inch plywood, and 2x6s for the legs. This table ended up serving us very well and a tower was constructed for the roles of material to sit on and poster board to create a smooth surface on the table.

FIG. 3. Box cutter (left), razor blade (center), and scissors (right)

FIG. 4. Table made in the lab with cut MLI for the 40 K stage of TSAT

Different types of adhesive were used with the majority being shown in FIG. 5. The Kapton is fine for lower blankets but not for blankets exposed to the blackbody from the outside. To ensure that our emissivity of the tape stayed low we use aluminized polyester tape which worked very well at covering the edges of the blankets and also securing them to each other.

EXPERIMENT

Our lab was sent a test cryostat from Penn that is shown in FIG. 6. This is comprised of a smaller cylinder

FIG. 5. Tape used in the construction of the MLI blankets. Thin and thick Kapton (left two) and Aluminized Polyester Tape (right)

that attaches to the first stage of our pulse tube and also a cylindrical outer chamber that can pull vacuum inside the cryostat so that convection heat transfer can not occur.

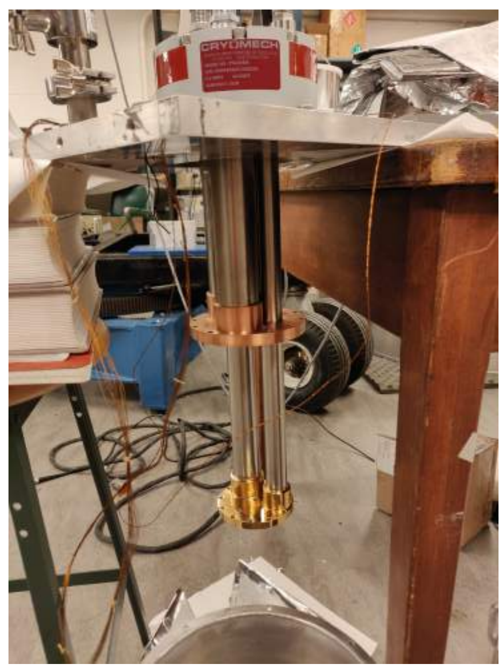

FIG. 6. Pulse tube set up in test cryostat without inner stage and outside vacuum shell

Next specific blankets were cut and then taped onto the cylinder that attached to the first stage of our pulse tube aka PTC 1. These blankets have 30 layers of aluminized mylar and are clocked so that the seems are not in the same location.

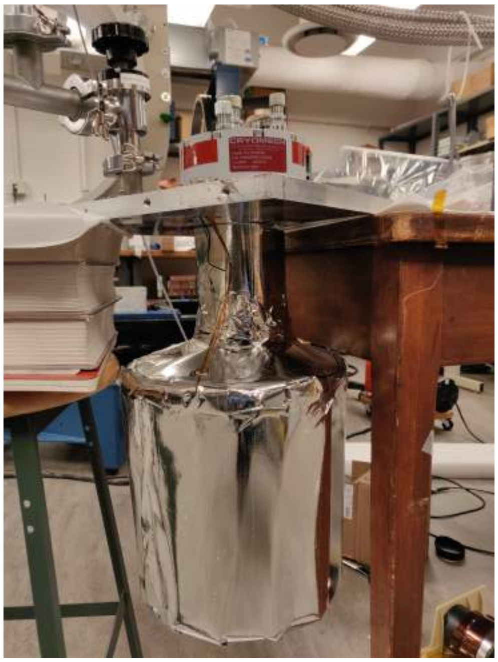

FIG. 7. Experiment setup before adding outer vacuum shell. 30 layers of blankets on the inner cylinder which is the PTC 1 stage

After the cooldown with the blankets, a heater was used to heat the blankets back to the temperature they reached without the blankets. This equation shows how the power the resistor supplied is related to the input voltage:

$$P = \frac{V_{app}^2 R_r}{(R_w + R_r)^2}$$

FIG. 8. An example of a 7 layer MLI blanket with the bottom looking normal and the top folded over to show the difference in the individual layers

RESULTS

The results of the experiment follow:
Load on PTC 1 without the blankets:

$$q_{nb} = 10.91W$$

Load on PTC 1 with the blankets:

$$q_b = .13W$$

Using these two numbers and the theoretical model the approximate effective emissivity of the blankets:

$$\epsilon_{eff} \approx .001$$

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