Thermal and Fluid Dynamics MacroProject: Space Blanket Analysis

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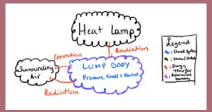
(JWST Sunshield Samples Provided by NASA Goddard Space Flight Center)

Introduction and Background

The goal of this investigation was to study a related aerospace system or components under the lens of a closed system. To wit, thermal blankets were chosen as ideal representation of a system attempting to emulate adiabatic properties. Thermal blankets act as near-perfect insulators for space-grade hardware of deployment joints, which may experience unwanted thermal stress through thermal cycling or just the extremely cold ambient conditions of space. When the idea of "near perfect" was mentioned, the concept of perfection lies with the theoretical notion of an adiabatic boundary, a facet of a system that does not allow any heat exchange across said boundary, and in situations where no work is done on the system, there is a lack of temperature change as well. Space-grade thermal blankets, such as the samples from the James Webb Space Telescope, do get very close to minimizing heat exchange to the point of obfuscating thermal risk and approaching that ideal. The experimental detailed below searches to analyze the concept of thermal blankets with aluminum foil acting as a placeholder for a thermal blanket.

System Diagrams

Figure 1: Control System | Figure 2: Analyzed System



System Equations

To begin with, the basic relation of closed systems, where the body's change in internal energy, $\dot{U}$, is equated to the difference in the isochoric one-dimensional change in heat, ∂Q, and the change in work, ∂W, is modeled.

$$\dot{U} = \partial Q - \partial w$$

Since the volume within the vessel is not being acted upon, the net work is null. Then each side is modified to equate the change in internal energy based on molarity, constant volume specific heat capacity and change in the body's temperature.

$$n_{vessel} \cdot c_{vessel} \cdot \frac{dT_B}{dt} = Q_{in} - Q_{out}$$

Since the system is observed at steady state, change is temperature is null. This means the input heat to equal the output heat.

$$0 = Q_{RAD-in} - (Q_{COND-OUT} + Q_{CONV-OUT} + Q_{RAD-OUT})$$

Since the area of conduction is very negligible, the system's output conduction can be abstracted out.
Also, since the power output of the heat lamp is known, there is no need to search for its output area of emissivity, but that 250-watt value needs to be scaled by the absorptivity, α, since the system is not considered a perfect black body.

$$0 = 250\alpha - hA_{CONV}(T_B - T_\infty) - \sigma\varepsilon_B A_{RAD-OUT} T_B^4$$

Additionally, the emissivity of the body, the area of contact for radiation and convection, and the room temperature, T_∞, can be found. Therefore, the only unknown is the temperature of the body, T_B.

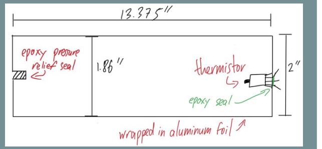
(Control) $250\ W(0.07) = 5.4 \frac{W}{m^2K}(0.0542\ m^2)(T_B - 297\ K) + 5.67010 \cdot 10^{-8} \frac{W}{m^2K^4}(0.07)(0.0542\ m^2)(T_B^4)$

(Analyzed) $250\ W(0.02) = 5.4 \frac{W}{m^2K}(0.0542\ m^2)(T_B - 297\ K) + 5.67010 \cdot 10^{-8} \frac{W}{m^2K^4}(0.02)(0.0542\ m^2)(T_B^4)$

System Construction

The system was built with one idea in mind: isolate the bodies temperature as much as possible. To wit, a tube body was milled, end caps were lathed and then welded together the main body. The end of the thermistor's jig was epoxied to its spot to assure a tight heat seal and that the thermistor could aptly collect data; the epoxy was also utilized to create pressure relief valve where the epoxy would pop out before the vessel collapsed.
While the original plan was to have an actual spring-actuated pressure relief valve(threads were tapped on the body), calculations showed that the pressure difference within the body, in the order of temperatures being tackled, would sum to around 1 atmosphere, which was not a major safety issue.

Figure 3: Preliminary Sketch of Pressure Vessel



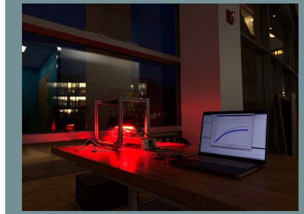


Figure 4: Experimental Set-Up

By constructing the system, the design choices for how the system was envisioned could be managed, and it facilitated the calculation of key metrics such as emissivity and area. To collect the data, the thermistor was connected to an Arduino pipeline, which would allow the server to collect data.
The set-up was designed to minimized failure issues and safety concerns. The final set-up, compared to previous designs, attempted to maximize the amount of area that was in contact with the air, engendering convection. Additionally, the separation between the beams and the body itself would mitigate any "heat chamber" effects that were observed and the data of previous experimental set-ups. Finally, the lamp itself was suspended in order to assure that no radiation would be lost directly to other supporting members, which was an issue in previous experimental set-ups.

Experimental Results

The data collection ran for about 5 hours. Each trial itself ran for about an hour while the cooling of the system, to assure constant system parameters, ran for about 45 minutes. By computing the experimental values through the control and analyzed system equations, theoretical model standards are used to compare the obtained experimental results.

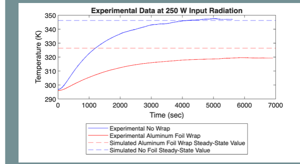


Figure 6: Comparison of Experimental and Theoretical Data for Control(No-Foil) and Analyzed(Foil) Cases

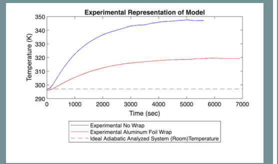


Figure 7: Verification of Hypothesis for Control(No-Foil) and Analyzed(Foil) Cases and Adiabatic Rest Temperature

As seen in *figure 7*, the data corroborates the initial model hypothesis: adding an aluminum foil pseudo-heat shield will protect the body from higher heat absorption and steady state temperatures. The steady state temperature for the analyzed foil case was much lower at closer to the ideal adiabatic steady state temperature compared to the steady-state temperature for the control no-foil case.

	No Wrap (K)	Wrap (K)
Theoretical	346.23	326.4
Experimental	347.03	319.26

Figure 5: Experimental vs. Theoretical Steady-State Temperature Values

In terms of representing the data purely in contrast between the experimental results and the theoretical projections, there does exist a contrasting gap between the theoretical and experimental steady-state temperatures for both the analyzed and control cases. As seen in *figure 6*, there also seems to be a contrast in how the experimental values differ from the theoretical bases: the analyzed case is under the theoretical value, and the control case is above the theoretical value. A reason for this difference may be due to a slight change in the room temperature, which would cause the latter analyzed foil experimental value to drop under the predicted theoretical value.

Error and Uncertainty

As mentioned in the "Experimental Results" section, even though the base relation is verified, there is definite error between the experimental and theoretical values. But before error is fleshed out, uncertainty must be discussed. In terms of the measurements, there is attached uncertainty to the area values since the tools are not always as precise as the constants taken from outside sources may be. Additionally, the model itself is not perfect as it make a multitude of assumptions, displayed in *figure 8*, that are believed to have smaller than significant impact on the desired values in the specific set-up, but are also difficult o model within the time constraints given.

While the data is not perfect, it does approach the theoretical model values in very appreciable fashion. Some other sources of error for the discrepancy between the theoretical and the experimental are in line with changing circumstances. At some point, the AC kicked down, and the room temperature cooled, which changed global parameters for the trials. Additionally, the heat lamp only covers a portion of the pressure vessel, and even then, not all the radiated heat from the lamp is transferred to the pressure vessel.

To fully understand how far away or values differ, and therefore if future iterations should consider some of the abstracted components of the model, the percentage error for both trials should be computed as such:

$$\%_{error} = \frac{|T_{Theoretical} - T_{Experimental}|}{T_{Theoretical}} \cdot 100$$

Following the equation's logic, the percentage error for the control case is around **0.2324%**, while the percentage error for the analyzed case is around **2.1883%**. These numbers are a major improvement compared to previous results by one order of magnitude. Considering the methodology for measuring the temperature is not overtly complex or lab precision, the respective percentage errors for both cases are quite low and fall under a very impressive precision realm.

In sum, the experimentation covered and trialed has a general accuracy for the expected data. Future iterations might consider suspending the body with a material with even lower conductivity than wood to mitigate conduction, and perhaps even restricting the dimensions of the vessel to only accommodate the area covered by the lamp's radiation. Even with inaccurate experimental data, the base hypothesis for understanding the use of thermal blankets as reflective insulators was proven with a corroborative relation between both experimental and theoretical data sets.

Data Collection Process

The collection of data stems from the heating of a heat lamp in two cases.

First a **control case**, where the **pressure vessel is heated at 250 watts**, where temperature is measured within the vessel through a thermistor connected to an Arduino pipeline.
In the **analyzed case**, the pressure vessel is covered by aluminum foil, which acts as the **heat blanket**.

the ideal situation would have the heat blanket act as a perfect adiabatic boundary, which would negate any heat exchange or temperature change(no work is done on the system). This means that the temperature is constant at room temperature for the entirety of the experiment's duration.

the goal is to show how the steady state temperature for the **analyzed case** is closer to the **ideal** situation constant temperature compared to the steady state temperature of the **control case**. *(fig.7)* demonstrates the data collection results.

Assumptions

To construct the model in a manner that was simple enough to trial, many assumptions were made. All of them are listed below, but further explanations are listed in the experiment appendix

Lumped Body	$\varepsilon = \alpha$ (Steady State)	No Internal Convection
Constant Q_{RAD-IN}	Constant Material Prop.	No Q Loss Through End Caps
Constant Room Temp.	Negligible Conduction	Negligible air Movement
Stand does not alter Convection	Foil has smooth and uniform surface	Initial Surface Temp. = Convection Temp
All Q_{Rad-IN} reaches the tube surface	Material Prop. are Approximated	Radiation from other objects is negligible

Figure 8: Assumption Table

NASA JWST Heat Shield Samples