

Characterizing Flow and Temperature Instabilities within Pulse Tube Cryocoolers Using Infrared Imaging

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ABSTRACT

Infrared (IR), or thermographic imaging, has long been used in general industry as a means of troubleshooting thermal, mechanical, and electrical systems. As IR imaging constructs a temperature map based on the infrared radiation a body is emitting, it is very useful at showing such things as friction points, heat leaks, electrical shorts, and at quickly performing such diagnostics that classical sensors have difficulty doing. In this paper we show how infrared imaging can also be used as a diagnostic tool in characterizing the flows and instabilities within Pulse Tube cryocoolers. While classical temperature sensors, such as thermocouples or diodes, may be indicative of the precise temperature at a specific point, they are quite limited in mapping a fully dynamic temperature profile resulting from some flow instability within the cryocooler. It is for such cases that IR imaging is quite helpful. IR imaging devices however do have limitations when employed in conjunction with cryocoolers, namely they are limited to imaging relatively high temperatures (those of 230 K and above) nevertheless they can still be a powerful diagnostic tool if used correctly. This paper will discuss some of the methods and points by which an IR camera can still be well utilized and will also present an actual example where IR imaging was used successfully as a diagnostic tool for quickly determining the source of detrimental flow within a pulse tube.

INTRODUCTION

In the past years infrared imaging technologies, initially developed for tactical and military use, have become much more widespread and are widely used in industry. One of the applications for which this technology has been found to be very useful is for system diagnostics. The primary reason for this is the fact that infrared imaging gives a very quick and relatively accurate thermal picture of the system being examined. In many cases of system malfunction, the cause will create a change in temperature profile of the system. This is true for an immense variety of systems from electronics through architecture and medicine. For example, when examining faulty circuit boards many of the faults will appear as a difference in component temperatures or for example when looking for cracks in roofing there are temperature discrepancies as a result of cold air leakage. The speed and simplicity at which these tests are made are the greatest advantage to use infrared imaging for troubleshooting and diagnostics and its speed and simplicity. It allows for the examiner to quickly assess the performance of the malfunctioning application without having to make contact

or add any additional sensors to the system. This imaging technique easily highlights system misbehaviors which can then quickly be translated into corrective solutions.

Given that cryocoolers are thermal systems, which when malfunctioning also respond with a distinct change in their thermal profile, one would expect that incorporating infrared imaging as a diagnostic tool in this field would also be very beneficial. There are inherent difficulties associated with trying to perform infrared imaging on cryocoolers, or for that matter on any cold objects, due to the fact that radiance decreases sharply with decreasing temperatures.

This paper will introduce the basic theory associated with infrared imaging and then discuss the difficulties in incorporating these methods with cryocoolers. Methods by which one may still utilize infrared imaging on cryocoolers will be presented along with a case study in which infrared imaging was employed to determine the source of flow instabilities in a high power Pulse Tube cryocooler.

INFRARED IMAGING – BASIC THEORY

Definitions

When infrared radiation is used to remotely determine the temperature of an object it is termed thermography. Thermographic cameras actually are radiation detectors for the infrared range of the electromagnetic spectrum (roughly 0.9–14 μm) and are designed to produce visual images that are representative of that radiation. Since infrared radiation is emitted by objects, as a function of their temperatures according to Planck's black body radiation law (which will be discussed in the next section), thermography in a sense makes it possible to "view" an object as a function of its surface temperature profile. It is important to remember that temperature is a derived parameter from the base radiation measurement. In the field of thermography the infrared spectrum is usually split into four subregions, each shortly defined below:

- **Near-infrared (NIR):** 0.75-1.4 μm , commonly used in fiber optic telecommunication.
- **Short-wavelength infrared (SWIR):** 1.4-3 μm , commonly used in long-distance telecommunications.
- **Mid-wavelength infrared (MWIR):** 3-8 μm , used in guided missile and homing technology.
- **Long-wavelength infrared (LWIR):** 8–15 μm , this region is generally referred to as the "thermal imaging" region, here sensors obtain a completely passive picture of target objects based upon their thermal emissions only and requiring no external light or thermal source. Forward-looking infrared (FLIR) systems use this area of the spectrum.

Radiance and spectral radiance are radiometric measures that describe the amount of light that passes through or is emitted from a particular area, and falls within a given solid angle in a specified direction. These terms are used to characterize both emission from diffuse sources and reflection from diffuse surfaces. The SI unit of radiance is watts per steradian per square meter ($\text{W}\cdot\text{sr}^{-1}\cdot\text{m}^{-2}$). Radiance characterizes total emission or reflection, while spectral radiance characterizes the light at a single wavelength or frequency. The radiance is equal to the sum (or integral) of all the spectral radiances from a surface. Spectral radiance has SI units $\text{W}\cdot\text{sr}^{-1}\cdot\text{m}^{-3}$ when measured per unit wavelength, and $\text{W}\cdot\text{sr}^{-1}\cdot\text{m}^{-2}\cdot\text{Hz}^{-1}$ when measured per unit frequency interval. Radiance is very useful and is generally used in thermography because it indicates how much of the power emitted by an emitting or reflecting surface will be received by an optical system looking at the surface from some angle of view.

To determine the radiance a body will emit as a function of temperature we employ Planck's law. Planck's law describes the spectral radiance of electromagnetic radiation at all wavelengths from a black body at temperature T . This law can be written more specifically in terms of the spectral energy density in units of energy per unit of volume for a given wavelength, λ :

$$u(\lambda, T) = 8\pi hc \frac{\lambda^{-5}}{e^{hc/\lambda kT} - 1} = C_1 \frac{\lambda^{-5}}{e^{C_2/\lambda T} - 1} \tag{1}$$

Where C_1 and C_2 are:

$$C_1 = 3.7 \times 10^{-12} \text{ W} \cdot \text{cm}^2, \quad C_2 = 1.44 \text{ cm} \cdot \text{K}$$

And h is Plank’s constant¹. Now, graphing this spectral radiance as a function of temperature and wavelength yields the graph shown in Figure 1. With the radiance scale being logarithmic it is obvious how rapidly the radiance emitted from an object decreases with a decrease in temperature. In fact from the graph one may see that there is very little radiance being emitted from objects at temperatures of 200 K and below.

Infrared Detectors

Radiometry, simply defined as an absolute measurement of radiant flux, is in fact what is employed by infrared imaging devices. The typical unit of measure for imaging radiometry is radiance [W/(sr-cm²)] which is defined above. There are different methods by which radiance can be quantified and measured. These methods are generally divided into two primary groups of detectors – thermal detectors and quantum detectors. These are described below:

- ◆ Thermal detectors - measure radiation by means of the change of temperature of an absorbing material.
 1. Thermocouple detector – the output in the form of a thermal *Electro-Magnetic Flux (EMF)*.
 2. Thermistor bolometer – a change in electrical resistance
 3. Pneumatic detector – the movement of a diaphragm caused by the expansion of a gas
- ◆ Quantum detectors – use effect of the quantum nature of radiation, i.e. Interaction of the radiation with electrons in solids causes the electrons to be excited to a higher energy state, in which electrical properties of the solid are different.
 - Photoemission – when electrons are given enough energy to escape from a solid and flow through a vacuum to give a current.
 - Photoconductor – n-type semiconducting material, which electrons can be excited to the conduction band leaving ‘holes’ behind in the valence band. Both excited electrons and the ‘holes’ are able to contribute to the conduction.
 - Photodiodes and phototransistors – if the absorption of the radiation occurs near a p-n junction, the excited carriers are swept away by the junction electric field and give a current in the external circuit.

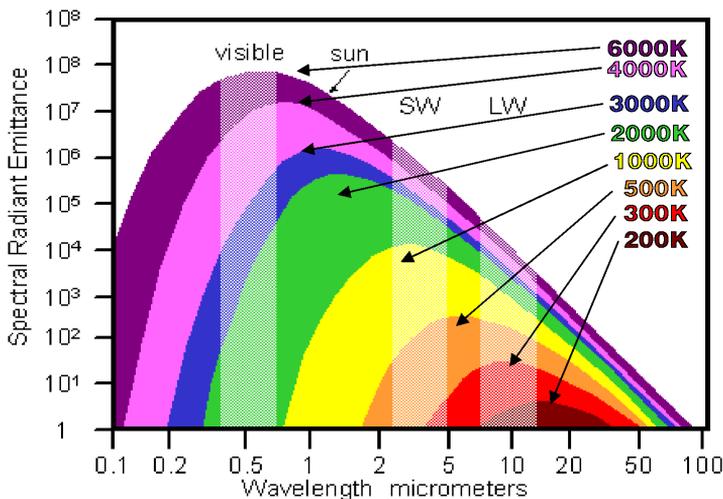


Figure 1. Spectral radiance as a function of wavelength for various temperatures.

The vast majority of high end infrared imaging devices use quantum detectors of the photodiode type.

Regardless of method however, with a decrease in the target object's temperature there is a decrease in available radiance to measure. This results in an inherent lower limit to the amount of radiance any detector will be able to accurately detect and translate into a temperature reading regardless of detector type. Figure 2 shows the "blackbody" calibration curve of a sample photodiode detector. Again we clearly see that as the object temperature continues to decrease there is an ever decreasing amount of available radiance for use in measuring and calibrating the sensors. Given this reality, of low available radiance at lower temperatures, which is linked to the inherent physics of infrared radiation it is clear why commercial infrared imaging devices cannot be used to view cryogenic bodies. They are generally used to image temperatures above about 230K. Despite this reality there is still ways in which these limitations may be circumvented to still allow infrared imaging to be employed in diagnosing a cryocooler at warmer temperatures. Two of these methods are discussed below.

METHODS TO IMAGE CRYOCOOLER SYSTEMS

Transient Imaging during Cool-down

A simple method to perform infrared imaging on a cryocooler is during the beginning stages of its cool-down. By imaging the beginning transient section of cool-down allows for the whole system to be imaged while it is still within the allowable temperature range. The imaging can occur up until that time when the cold heat exchanger drops below the detection range of the infrared camera (typically in the vicinity of 230 K~240 K). This method has the advantage of being very quick and yet still gives a good indication of the developing thermal profiles on the cryocooler. As this is a relatively short transient test, the cryocooler can be imaged while exposed to the environment without need for further complexities associated with vacuum cans and infrared viewing ports. The big disadvantage to this method is that only the initial transient profiles are being imaged and they behave slightly differently than those profiles at steady state. However in many cases the offending instability is already easily visible from start-up. Attention must be given to two important points while employing this method – (1) frost/condensation buildup on surfaces once the surface temperatures have started to drop. Frosted or wet surfaces cause the surface emissivity to change considerably thus masking the actual cryocooler surface temperature. However, as long as these tests are short, on order of 1-3 minutes, frost and condensation should not pose a serious problem. (2) Radiation shielding such as Mylar sheets should also be used when exposed to the environment. Without the radiation shielding the infrared camera will pick up considerable amounts of reflecting radiation from other sources, such as lab equipment or even the researcher (who is also radiating in the 8–15 μm wavelength).

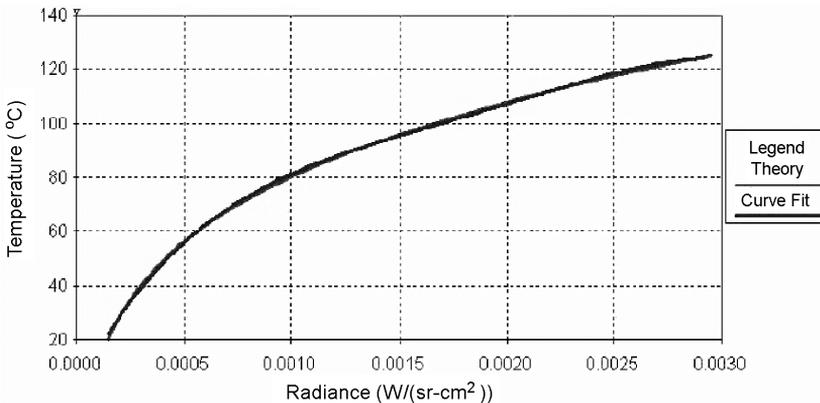


Figure 2. "Blackbody" calibration curve (radiance to temperature) for a photodiode infrared sensor

Steady State Imaging while Heat Loading

Another method to perform infrared imaging which does permit the imaging of the steady-state thermal profiles on the cryocooler is to perform imaging while the cryocooler's cold heat exchanger is being heat loaded. A heat load is applied to the cold heat exchanger so as to stabilize the cold end of the Pulse Tube at about 230 Kelvin (or whatever the lower limit of the camera is). In this way the Pulse Tube stabilizes to steady-state operating conditions while still being completely within a temperature range that is visible to the infrared camera. The important points to pay attention to in this method are: (1) The Pulse Tube should be viewed inside a vacuum to prevent any "frost" build up on the surfaces while steady-state imaging is occurring and (2) the camera will need view the cryocooler through an appropriate infrared viewing port such as a Germanium window (which is relatively transparent at 8–15 μm). The benefits of this method are that the developed steady-state thermal profiles are being imaged. The disadvantage of this method is that the performance characteristics of the cryocooler, due to differences in enthalpy flow and material properties at these warmer temperatures, are going to be unlike those at cryogenic temperatures. In general however, if there is a blatant thermal instability caused by cryocooler malfunction (such as a Helium leak, bad geometry, insufficient heat transfer, etc.) it will to some extent be visible to the infrared camera even if the cryocooler is being run at a higher temperature range. This will not be the case if the instability is caused or occur only at the lower temperatures themselves as would be the case for example in a cold-seal gas leak, which only develops once at cryogenic temperatures.

CASE STUDY – INFRARED DIAGNOSTICS ON A HIGH POWER PULSE TUBE

Case Background

The whole topic of infrared imaging actually came about in an attempt to determine the cause for some significant thermal instability in a newly designed high power Pulse Tube at NIST, shown in Figure 3. The Pulse Tube designed and assembled at NIST was intended to provide 50 watts of cooling at 50 K for an input power of 2.5 kW. In reality this high power single stage Pulse Tube had difficulty reaching temperatures below 100 K and instead exhibited very unstable behavior. Initially, in an effort to source the problem, the Pulse Tube was blanketed with 16 thermocouple sensors at various cross sections of the regenerator and buffer tube in the hope that they would shed light on the source of the instability. In fact the thermocouple measurements, which were "across the board" in terms of values and also unstable, were not helpful in pinpointing the problem at all (other than illuminating the fact that there was a serious flow problem). As a result of this lack of productive information, infrared imaging was brought up as a possible method of sourcing the problem.



Figure 3. High power Pulse Tube intended to provide 50 W of cooling at 50 K which instead exhibited very unstable behavior and no load cold temperatures of ~ 100 K.

Infrared Imaging of Pulse Tube

As the instabilities being observed by the temperature sensors were quite significant and also appeared immediately with start-up the method of measuring the transient temperature profiles in open air was adopted. The cryocooler was filmed with an infrared video camera from just before start up until the cold heat exchanger dropped below 240 K, this took about 2 minutes. Figure 4 shows the resulting infrared image of two opposite faces of the buffer tube. Even though the dynamic video image is quite impressive as it shows the dynamic onset of the instability it is obvious to see from this figure that there is an impinging jet hitting the buffer tube about a third of the way down the buffer tube, as shown in (a), which results in a completely asymmetric flow profile across the buffer tube which is shown in (b). Figure 5 shows the camera setup and the Mylar radiation shielding.

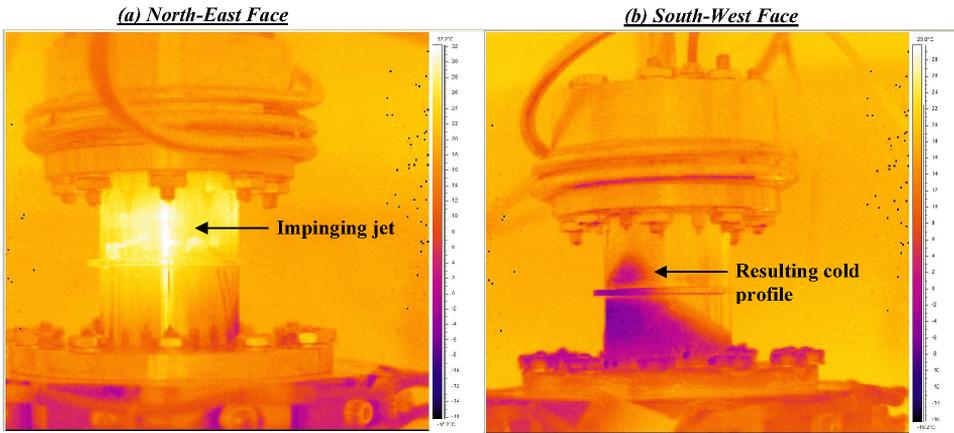


Figure 4. Infrared images of the buffer tube (a) North-East Face showing impinging jet (b) South-West Face showing the resulting flow instability.

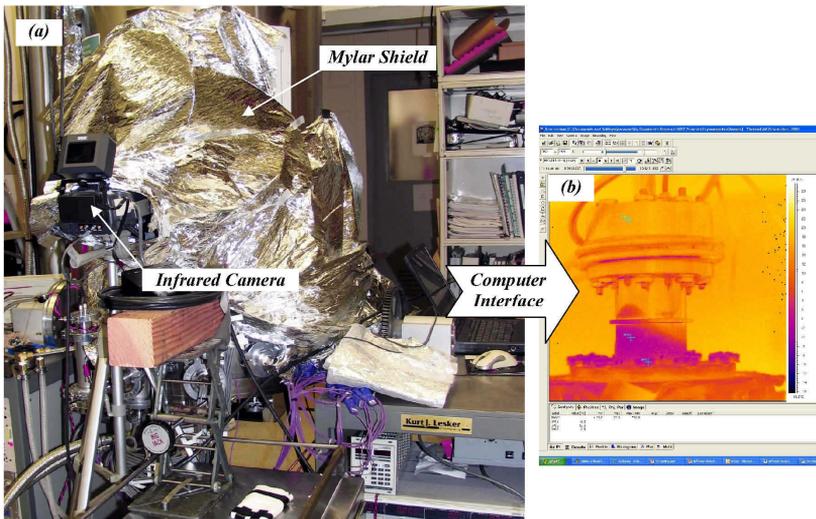


Figure 5. (a) Infrared camera setup to film Pulse Tube during first stages of cool-down. (b) screen shot of computer interface.

Determining Malfunction and Corrective Measures

As the infrared images shown in figure 4 illustrate the source of the problem quite clearly it was then a simple task to disassemble the Pulse Tube and directly focus our attention to the area from which the jetting was occurring. To accommodate the relatively high heat fluxes needing to be dissipated from the warm and cold heat exchanger they were initially designed with a quad geometry as seen in Figure 6a. Each heat exchanger had 4 copper screen stacks, each individually cut and diffusion bonded into the copper holding plate. As it turns out, after disassembly, these copper screen stacks had not diffusion bonded well with each other or the copper plate, and specifically, one of these stacks had come almost completely loose. It was from this quadrant that the jetting was most pronounced. To correct the problem new copper screen stacks were cut and re-diffusion bonded into the quadrants in such a fashion to improve their contact and hold. Figure 7 shows an infrared image of the North-East face after these corrective measures were incorporated into the pulse tube. As can be seen, these corrective measures clearly improved the instability.

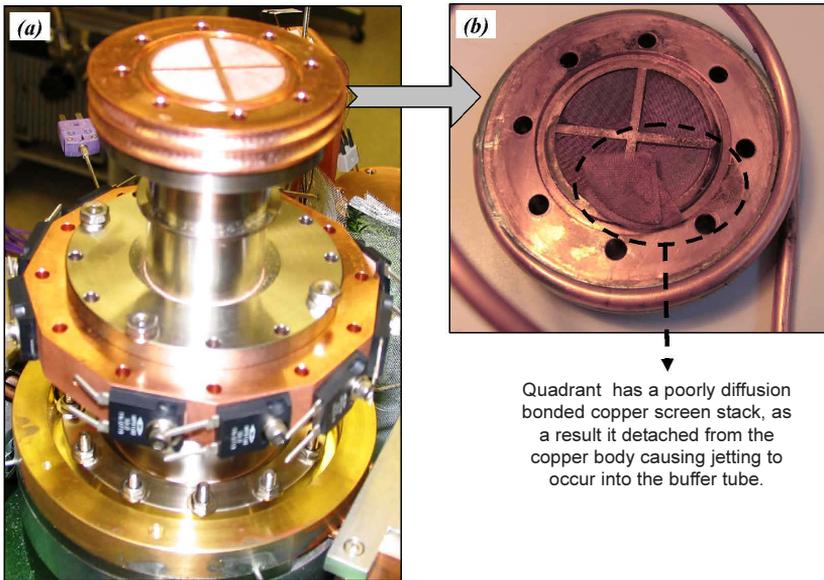


Figure 6. (a) Disassembled Pulse Tube showing the warm heat exchanger with its quadrant design (b) warm heat exchanger showing the poorly bonded copper screen stack responsible for the jetting.

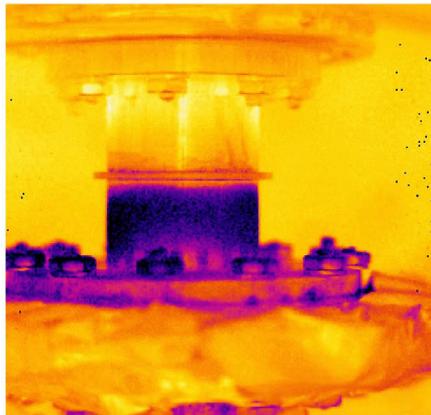


Figure 7. Infrared image of the northeast face of the buffer tube during cool-down.

CONCLUSION

Due to the inherent limitations of infrared imaging it may not be used as an accurate measurement tool in cryogenic applications. However, as there are many instances that a quick and simple diagnostic tool is very useful to determine the source of some thermal instability, infrared imaging should still be considered a valuable additional method for evaluating pulse tube performance. As is shown in the case study presented in this paper infrared imaging may not be extremely precise but, if used correctly, may still serve as a very useful tool in cryocooler diagnostics.

ACKNOWLEDGMENT

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