LEOI-65 Experimental Apparatus of Thermal Radiation and Infrared Thermography

Theory

1) **Thermal Radiation and Blackbody Radiation Theory**

In the 19th century, key advancements were made in the study of thermal radiation. In 1858, Balfour Stewart's experiments revealed that an object's ability to radiate is correlated with its absorptivity. Lampblack surfaces exhibit the strongest emission and absorption, and the radiation characteristics follow Helmholtz's reciprocity principle, indicating a mutual relationship between emission and absorption properties.

In 1859, Kirchhoff proposed the law of thermal radiation, stating that at thermal equilibrium, the ratio of an object's emissivity to its absorptivity is a universal function, independent of the material. That is, at the same temperature, the ratio of monochromatic emissive power $M(\lambda,T)$ to monochromatic absorptivity of a radiating body $\alpha(\lambda,T)$ depends only on a function $f(\lambda,T)$ of the **wavelength** λ and **temperature** T, and can be expressed as:

$$\frac{M(\lambda,T)}{\alpha(\lambda,T)} = f(\lambda,T). \tag{1}$$

A body whose emission matches this function $\alpha(\lambda,T)=1$ at all wavelengths is called an *ideal blackbody*, or simply *blackbody*. The blackbody emits uniformly in all directions, thus it is a perfect Lambertian (cosine) emitter. Objects with emissivity less than a blackbody, but whose emission intensity at each wavelength remains proportional to the corresponding blackbody intensity at the same temperature, are known as *gray bodies*. Absolute blackbodies and gray bodies do not exist in nature; real materials exhibit wavelength-dependent emission—called *selective radiators*. However, over narrow wavelength ranges, materials can be approximated as gray bodies.

In 1879, **Stefan** empirically discovered that the total emissive power of a blackbody is proportional to the fourth power of its absolute temperature. In 1884, **Boltzmann** provided a rigorous theoretical proof. The mathematical expression is:

$$M(T) = \sigma T^4. \tag{2}$$

This is the **Stefan–Boltzmann Law**, where $M(T)$ is the total emissive power, T is the thermodynamic (absolute) temperature, and $\sigma = 5.67032\times10^{-8} W\cdot m^{-2}\cdot K^{-4}$ is the Stefan–Boltzmann constant.

In 1893, **Wien**, supported by thermodynamics, spectroscopy, electromagnetism, and optics, proposed the **Wien's Displacement Law**, stating that the product of the absolute temperature of a blackbody and the wavelength at which its emissive power peaks is a constant:

$$\lambda_m T = b, \tag{3}$$

where λ_m is the wavelength corresponding to the peak emission, and $b = 2.89777\times10^{-3} m\cdot K$ is **Wien’s constant**. This law indicates that as a blackbody's temperature increases, its peak radiation shifts toward shorter wavelengths. Wien’s law agrees with the short-wavelength portion of blackbody radiation curves and is applicable across the entire emission spectrum. It represents the most comprehensive insight into blackbody radiation available from classical physics.

In 1900, British physicist **Rayleigh**, based on the equipartition theorem, derived the **Rayleigh–Jeans law** for blackbody radiation energy distribution:

$$u(\upsilon,T) = \frac{8\pi kT}{c^3}\upsilon^3 , \tag{4}$$

where $u(\upsilon,T)$ is the spectral energy density, $k = 1.38066\times10^{-23} J/K$ is Boltzmann’s constant, c is the speed of light in a vacuum, and υ is the frequency of the radiation. While this formula agrees with experiments at long wavelengths, it diverges at short wavelengths where it predicts infinite energy—a problem historically termed the **"ultraviolet catastrophe"**, which exposed the limitations of classical physics and catalyzed the development of modern physics.

Also in 1900, **Planck**, building on prior work, used interpolation to reconcile Wien’s and Rayleigh–Jeans’ formulas, and derived a formula that agreed with experimental data across all wavelengths:

$$\rho(\upsilon,T) = \frac{8\pi\upsilon^2}{c^3}\frac{h\upsilon}{e^{\frac{h\upsilon}{kT}}-1} , \tag{5}$$

where $h = 6.62676 \times 10^{-34} J \cdot s$ is **Planck’s constant**. Planck's formulation led him to propose the groundbreaking **quantum hypothesis**: electromagnetic radiation of frequency υ is emitted or absorbed in discrete units (quanta) of energy $E = h\upsilon$. These indivisible energy packets are called **energy quanta**.

Planck’s radiation law matched both theory and experiment, accurately explaining blackbody radiation phenomena. It converges with Rayleigh–Jeans at low frequencies and avoids the ultraviolet catastrophe at high frequencies. Planck’s work is one of the cornerstones of **quantum physics**, introducing the concept of **energy quantization**, which laid the foundation for quantum mechanics. Although initially viewed as a mathematical trick, Planck’s quantum hypothesis was later expanded by Einstein and others, becoming central to modern quantum theory.

2) **Factors Affecting Thermal Radiation Transmittance in Media**

a) **Absorption Properties**

Different materials absorb thermal radiation to different extents. According to Planck’s law, thermal radiation energy depends on both temperature and wavelength. A material’s absorption depends on its molecular structure and electron energy levels, meaning its absorption varies across wavelengths.

b) **Reflective Properties**

A material’s reflectivity also influences transmittance. Per Kirchhoff’s law, an object’s absorptivity and emissivity are numerically equal. Therefore, highly reflective materials tend to have lower transmittance.

c) **Transmission Characteristics**

A medium’s transmittance results from the combined effects of absorption and reflection. Solids and liquids, due to dense molecular structures, usually block radiation and thus have low transmittance. Gases, with greater molecular spacing, typically have higher transmittance. For instance, air transmits thermal radiation well, while water vapor absorbs strongly at certain wavelengths.

d) **Microscopic Structure**

At the microscopic level, thermal radiation propagates through media in accordance with Maxwell’s equations. Interaction between radiation waves and particles (like electrons or ions) alters the radiation's direction. These interactions vary by material, leading to distinct macroscopic radiation properties.

e) **Material Thickness**

Thicker media increase the path length of radiation, enhancing absorption and scattering, which reduces transmittance.

3) Infrared Thermal Imagers

Infrared thermal imagers detect thermal radiation emitted by objects using infrared detectors that convert the incoming radiation into electrical signals. Common types include **HgCdTe (Mercury Cadmium Telluride)**, **InSb (Indium Antimonide)**, and **microbolometers**.

The electrical signals are amplified and digitized, then processed into grayscale or pseudo-color images that reflect surface temperature or radiation distribution. Thus, thermal imagers provide visual representations of an object’s thermal state.

Thermal radiation spans wavelengths from 0.75 μm to 1000 μm. Infrared imagers typically operate in the **8–14 μm** range, which allows good atmospheric penetration and is widely used in thermal imaging.

Environmental factors such as atmospheric conditions and surface reflectivity affect image accuracy and measurement precision.

4) Influence of Emissivity on Infrared Thermographic Measurements

Emissivity is the ratio of energy emitted by a surface to that emitted by a blackbody at the same temperature. A perfect blackbody has emissivity 1. Real materials vary based on composition, surface texture, shape, viewing angle, wavelength, and temperature.

Objects with **high emissivity** (like wood, fabric, or human skin) emit infrared radiation efficiently, making their temperature easier to measure accurately. For example, human skin has an emissivity around 0.98.

Objects with **low emissivity** (like polished metals) reflect more environmental radiation, potentially skewing infrared readings. For example, polished copper or aluminum may have emissivity below 0.10, reflecting surroundings like a mirror.

Therefore, **correct emissivity settings** are critical for accurate temperature readings.

5) Measuring Emissivity Using Infrared Thermography

Thermal imagers determine temperature by detecting emitted radiation. In practice, the total radiation detected includes: Emitted radiation from the object, Reflected environmental radiation, and Atmospheric radiation.

The detected radiation intensity is:

$$W_\lambda = \varepsilon_\lambda W_{b\lambda}(T_0) + \rho_\lambda W_{b\lambda}(T_u) = \varepsilon_\lambda W_{b\lambda}(T_0) + (1-\alpha_\lambda) W_{b\lambda}(T_u) \ , \qquad (6)$$

where: the 1st term is the radiation from object surface, the 2nd term is the radiation from the environment, T_0 is the object temperature, T_u is the equivalent radiation temperature of environment. ε_λ , ρ_λ and α_λ are respectively emissivity, reflectivity and absorptivity of object surface.

The formula for temperature measurement of infrared thermal imagers is given by:

$$f(T_r) = \tau_a \left[\varepsilon f(T_0) + (1-\alpha) f(T_u) \right] + \varepsilon_a f(T_a) \ , \qquad (7)$$

Where: T_r is the indicated radiation temperature, τ_a is atmospheric transmittance, ε_a is atmospheric emissivity, T_a is atmospheric temperature.

When the measured surface is a blackbody, the atmospheric transmittance $\tau_a = 1$, and the emissivity $\varepsilon_a = 0$, then the radiation temperature indicated by the thermal imager is equal to the true surface temperature of the object $f(T_r) = f(T_0)$.

When ε<1, the radiation temperature indicated by the thermal imager is **not** equal to the true temperature of the object. In equation (7), if $\alpha = \varepsilon$, meaning the measured object can be considered a gray body, and $\varepsilon_a = 1 - \tau_a$, then the following holds:

$$f(T_r) = \tau_a \left[\varepsilon f(T_0) + (1-\varepsilon) f(T_u) \right] + (1-\tau_a) f(T_a) \ . \qquad (8)$$

Eq. (8) is the basic formula for calculating temperature of a thermal imager.

From Planck's formula (5), converting frequency to wavelength for thermographic applications:

$$f(T)=\int_{\Delta\lambda} R_\lambda W_{b\lambda}(T)d\lambda=\int_{\Delta\lambda} R_\lambda \frac{C_1}{\lambda^5}\frac{1}{e^{\frac{C_2}{\lambda T}}-1}d\lambda \ , \tag{9}$$

Where: $C_1=2\pi hc^2=3.7418\times10^{-16}W\cdot m^2$ is the first radiation constant, $C_2=\dfrac{ch}{k}=1.4388\times10^{-2}m\cdot K$ is the second radiation constant, and R_λ is the spectral response of the imager.

When ignoring the wavelength dependence of R_λ , integrating (9) yields the approximate temperature relation:

$$f(T)\approx CT^n \ . \tag{10}$$

when wavelength is between $2\sim5\mu m$, $C=7.2768\times10^{-23}$, $n=9.2554$; wavelength is $8\sim13\mu m$, $C=1.9675\times10^{-8}$, $n=3.9889$.

Placing (10) into (7), the emissivity is:

$$T_r^{\ n}=\tau_a\left[\varepsilon T_0^{\ n}+(1-\alpha)T_u^{\ n}\right]+\varepsilon_a T_a^{\ n} \ . \tag{11}$$

When using thermal imagers operating in different wavelength bands, the value of *n* varies.

For short-distance measurements, it can be assumed that the atmospheric transmittance $\tau_a=1$, and the atmospheric emissivity $\varepsilon_a=0$. If the surface of the measured object satisfies the **gray body approximation**, i.e., $\varepsilon=\alpha$, then the object's **emissivity** can be calculated using Equation (12):

$$\varepsilon=\frac{T_r^{\ n}-T_u^{\ n}}{T_0^{\ n}-T_u^{\ n}} \ . \tag{12}$$

For the thermal imager included in the LEOI-65 apparatus, $n=3.9889\approx4$, as long as the radiation temperature indicated by the thermal imager T_r, the actual temperature of the object T_0, and the ambient temperature T_u are known, the emissivity of the object can be calculated using Equation (12).