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Infrared imaging - case studies and applications

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ABSTRACT

INFRARED IMAGING – CASE STUDIES AND APPLICATIONS

By
Shuang Du

Recent advancements in the manufacture of solid state detectors have led to significant improvements in the use and applications of infrared (IR) imaging. Compared with traditional imaging in visible light, infrared imaging has abilities to convey significant additional information. Applications in medicine require wavelengths in the range of 0.8 to 25 microns while metrology and astronomy, traditionally, require wavelengths in the range of 25 microns to 1 mm.

In this study, infrared imaging has been used as a tool to characterize a variety of objects and systems. Some of these case studies have been considered under conditions of thermodynamic non-equilibrium. The results obtained are analyzed by considering the radiative properties of various materials.

INFRARED IMAGING – CASE STUDIES AND APPLICATIONS

By
Shuang Du

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APPROVAL PAGE

INFRARED IMAGING – CASE STUDIES AND APPLICATIONS

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From left to right: Shuang Du, Dr. N. M. Ravindra and Ruolei Liu.

If you are my teacher for even one day, you will be my mentor all my life.

一日为师，终身为师。

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CHAPTER 1

INTRODUCTION

From a general point of view, in many army movies, we can watch the use of IR (Infrared) radiation to detect warm bodies. The IR (Infrared) heat that is emitted from an object is detected with a thermal imaging device, and leads to difficulties to avoid the detection of objects including army personnel. Originally, these infrared imaging technologies were developed for military use during wars. More recently, infrared imaging technology has several applications, such as night vision, moisture detection in walls and roofs, and search and rescue operations. Infrared is invisible radiant energy, electromagnetic radiation with longer wavelengths than those of visible light, extending from the nominal red edge of the visible spectrum at 700 nanometers (frequency 430 THz) to 1 mm (300 GHz). [1] If one could see these waves, they are only 0.00074 to 0.3 millimeters (0.00004 inches to 0.01 inches) of wavelength. The wavelength of visible light is only 300 to 700 nanometers, which is far narrower than infrared wavelength. Therefore, infrared imaging technology has enormous capabilities.

Recently, more and more researchers focus on infrared applications. Some of them contribute to research on materials that can avoid detection from infrared sensors. Other researchers have applied their research to detect someone or something by utilizing infrared device. There is no absolute and certain way to overcome infrared. Only a few techniques can make detection more difficult. In this thesis, we will explore and discuss infrared imaging of various objects and materials by experiments.

CHAPTER 2

FUNDAMENTALS OF OPTICAL PROPERTIES OF MATERIALS

2.1 Refractive Index

In optics, the refractive index n of a material describes how light propagates through that medium. It is a dimensionless number. From Snell's Law[2], we find the relationship between the refractive index and wavelength.

$$n = \frac{c}{v} = \frac{c/f}{v/f} = \frac{\lambda_0}{\lambda} \tag{2.1}$$

where c is the speed of light in vacuum and v is the phase velocity of light in the medium. λ_0 is the wavelength in a medium, λ is the wavelength in vacuum. f is the frequency.

In equation (2.1), the frequencies are canceled because they do not change when light travels from one medium to another.

2.2 Extinction Coefficient

When light propagates through a medium, it is often attenuated or absorbed. Extinction coefficient κ is the value of attenuation when the electromagnetic wave passes through the material. By defining a complex refractive index, it can be conveniently taken into account in (2.2)

$$n = n + i\kappa. \tag{2.2}$$

Here, the real part n of equation (2.2) is the refractive index and indicates the phase velocity, while the imaginary part κ means the extinction coefficient.

2.3 Absorptance

In physics, absorption of electromagnetic radiation is the way in which the energy of a photon is taken up by matter, typically the electrons of an atom. This transforms the internal energy (for example, thermal energy[3]) of the absorber into the electromagnetic energy. Absorptance of the surface of a material is its effectiveness in absorbing radiant energy. It is the fraction of incident electromagnetic power that is absorbed at an interface, in contrast to the absorption coefficient, which is given by equation (2.3).

The absorption coefficient α is related to the extinction coefficient κ by the formula (2.3).

$$\alpha = \frac{4\pi\kappa}{\lambda} \tag{2.3}$$

where λ is the wavelength.

2.4 Reflectance

Reflection is the change in direction of a wave and makes the wave to return into the original medium. It is a measure of the effectiveness of the surface of a material in reflecting radiant energy. The reflectance ρ is related to the fundamental optical parameters, n and κ.[4]

$$\rho = \frac{(n-1)^2 + \kappa^2}{(n+1)^2 + \kappa^2} \tag{2.4}$$

where n is the refractive index and κ is the extinction coefficient.

2.5 Transmittance

Transmittance of the surface of a material is its effectiveness in transmitting radiant energy. Internal transmittance is that due to energy loss by absorption, and total transmittance refers to absorption, scattering, reflection, etc. Transmittance τ can also be related to the fundamental optical parameter α.[4]

$$\tau = \exp(-\alpha t) \tag{2.5}$$

where α is the absorption coefficient expressed in units of reciprocal of length.

Accepting equation (2.3),

$$\tau = \exp(-\alpha t) = \exp(-\frac{4\pi\kappa}{\lambda}t) \quad (2.6)$$

When the surface of a material is penetrated by radiation, the total energy must be divided into three parts. The proportions of them are reflectivity (ρ), absorptivity (a) and transmissivity (τ) (see Figure 2.1). The relationship governing them is as in equation (2.7).

$$\rho + a + \tau = 1 \quad (2.7)$$

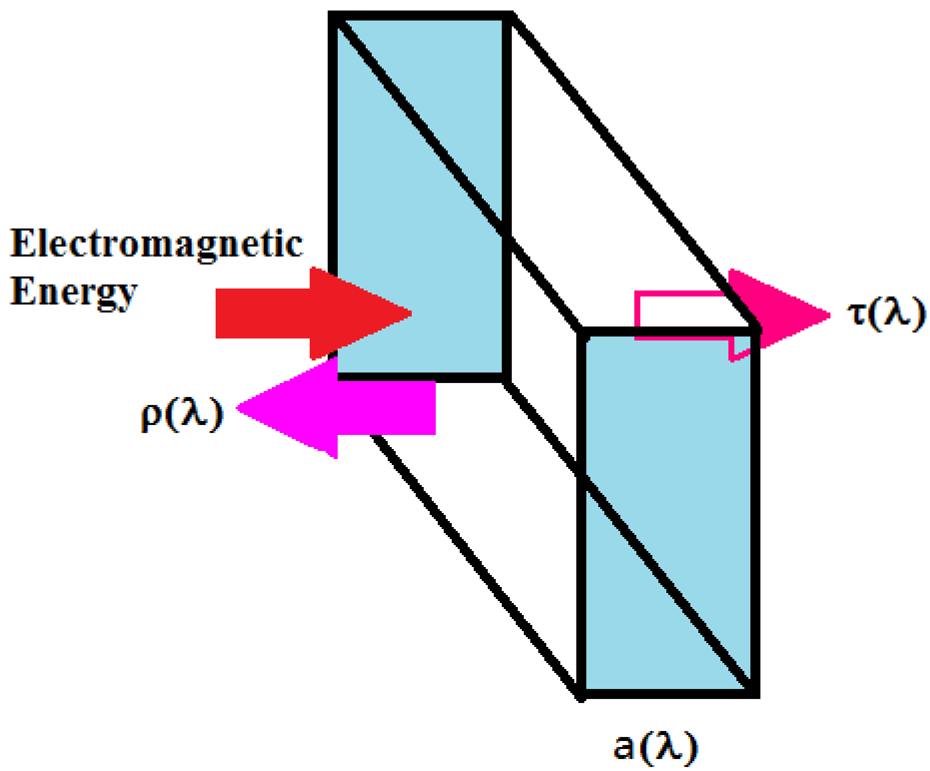


Figure 2.1 Absorptance a(λ), reflectance ρ(λ) and transmittance τ(λ).

2.6 Transparency, Translucency and Opacity

In the field of optics, transparency (also called pellucidity or diaphaneity) is to allow light to pass through the material without being scattered. It can be seen through the transparent material; that is, they allow clear images to pass through. Translucency (also called translucence) is a super-set of transparency. Translucent material allows only light scattering penetration, that is, the material will distort the image. Although transparent usually refers to the visible light, it can properly refer to any type of radiation. For example, the body is transparent to X-rays, but not the bones. X-ray imaging is a very useful technique in monitoring health as well as in several applications.

Opacity is a measure of impenetrability to electromagnetic or other kinds of radiation, especially visible light. It describes the absorption and scattering of radiation in a medium, such as a plasma, dielectric, shielding material, glass, etc. As was discussed in section 2.5, light may be reflected, absorbed, scattered, and the rest transmitted. For example, a white wall, or a specular surface can reflect light. Without light being transmitted, an opaque body can reflect, scatter, or absorb all of light. Both mirrors and carbon black are opaque. Like transparency and translucency, opacity depends on wavelength of radiation such as in some types of glass. While transparent in the visual range, they are largely opaque in ultraviolet range.

Transparency, Translucency and Opacity can be quantified by absorptance, reflectance and transmittance.

1. Opaque body, $\tau = 0$, $a + \rho = 1$.

2. Transparent body, $\tau = 1$, $a = \rho = 0$.

3. Translucent body, $0 < \tau < 1$, $0 < a + \rho < 1$.

4. Black body, $\tau = 0$, $a = 1$, $\rho = 0$.

CHAPTER 3

BLACK BODY RADIATION

3.1 Electromagnetic Spectrum

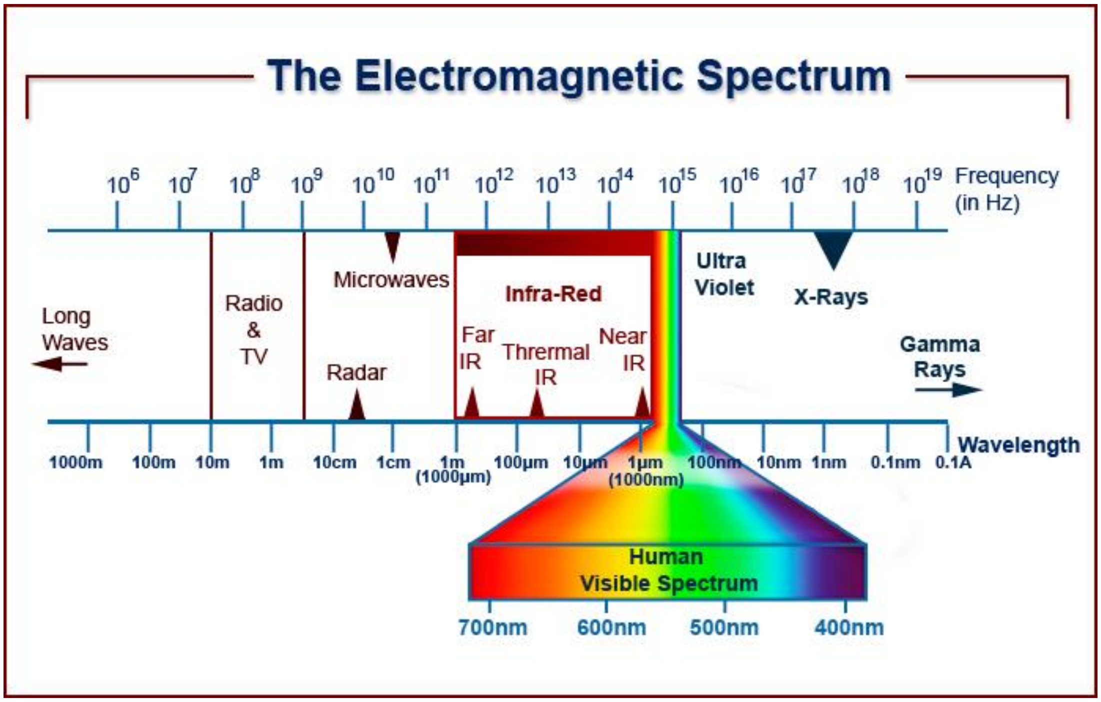


Figure 3.1 Electromagnetic spectrum.

Source: http://contemporarymedicine.net/intergrative-therapies/

The electromagnetic spectrum is divided arbitrarily into a number of wavelength regions, called bands, distinguished by the methods that are used to produce and detect the radiation. There is no fundamental difference between radiations in the different bands of the electromagnetic spectrum. They all follow the same laws and the only difference is that due to different wavelengths.

3.2 Radiation

Infrared radiation is electromagnetic radiation in the form of heat. In thermodynamic equilibrium, radiation surrounding a body transfers heat to its environment. It does not depend on any external condition and only on the temperature of the object. Thermal radiation is one of the three main heat transmission methods. Infrared radiation in the spectral distribution of a black body is usually considered as a form of heat, since it has an equivalent temperature and is associated with an entropy change per unit of thermal energy. A black body, which is an opaque and non-reflective body, can emit radiation at constant temperature. [5]

3.3 Black Body

A blackbody appears black at room temperature. An object that emits or absorbs radiation at all wavelengths is called as a black body. The Kirchhoff's law of thermal radiation explains the spectral characteristics of black bodies. Kirchhoff's law refers to wavelength-specific radiative emission and absorption by an object in thermodynamic equilibrium, including radiative exchange equilibrium.[5] "According to the law of Kirchhoff, the ratio of the radiation power to absorbing power is the same for all bodies at the same temperature, and therefore a body which absorbs perfectly must radiate perfectly." [6] As Kirchoff's law states, an ideal black body often refers to an ideal radiator.

Most of the radiation of a black body is infrared and cannot be noticed by human eyes. This is because a black body is the least visible at very low light intensities so that human eyes cannot perceive color in the dark. The black body subjectively appears grey. Black-body radiation has a continuous frequency spectrum which only depends on the temperature of the body, [7] called the Planck spectrum or Planck's law.

3.4 Planck's Law

Planck's law describes the electromagnetic radiation emitted by a black body in thermal equilibrium at a definite temperature. The law is named after Max Planck, who originally proposed it in 1900. It is a pioneering result of modern physics and quantum theory.

The spectral radiance of a body, W_ν, describes the amount of energy it gives off as radiation of different frequencies. It is measured in terms of the power emitted per unit area of the body, per unit solid angle that the radiation is measured over, per unit frequency. Planck showed that the spectral radiance of a body at absolute temperature T is given by:

$$W_\vartheta = \frac{2h\vartheta^3}{c^2} \frac{1}{e^{\frac{h\vartheta}{k_B T}} - 1} \quad (3.1)$$

where k_B is the Boltzmann constant, h is the Planck constant, and c is the speed of light in the medium, whether material or vacuum. [8, 9] The spectral radiance can also be measured per unit wavelength instead of per unit frequency.

Planck's law describes the spectral distribution of the radiation from a blackbody. In this case, it is given by, [10]

$$W_\lambda = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1} \quad (3.2)$$

where W_λ is blackbody spectral radiant emittance at wavelength λ. c is the velocity of light (3 x 10^6 m/s). h is Planck's constant (6.6 x 10^{-34} joule sec). k_B is Boltzmann's constant (1.4 x 10^{-23} joule/K). T is absolute temperature (K) of a blackbody and λ is Wavelength (µm).

Planck's law may also be expressed in other terms, such as the number of photons emitted at a certain wavelength, or the energy density in a volume of radiation. The SI units of W_ν are W sr^{-1} m^{-2} Hz^{-1}, while those of W_λ are W sr^{-1} m^{-3}.

In the limit of low frequencies (i.e., long wavelengths), Planck's law approaches the Rayleigh–Jeans law, while in the limit of high frequencies (i.e., small wavelengths), it tends to the Wien approximation.

Max Planck developed the law in 1900, originally with only empirically determined constants. Planck later showed that, expressed as an energy distribution, it is the unique stable distribution for radiation in thermodynamic equilibrium. [8]

3.5 Stefan-Boltzmann Law

Integrating the Planck's formula from λ=0 to λ=∞, we obtain the formula (3.3) [11],

$$W_b = \sigma T_1^{\,4} \tag{3.3}$$

where W_b is the total radiant emittance of a blackbody. T is the blackbody's thermodynamic temperature. σ is the Stefan-Boltzmann constant or Stefan's constant. It can be obtained from other constants.

$$\sigma = \frac{2\pi^5 k^4}{15c^2h^3} = 5.670373 \times 10^{-8}\, Wm^{-2}K^{-4} \tag{3.4}$$

where k is the Boltzmann constant. h is the Planck's constant and c is the speed of light in vacuum.

An object that cannot absorb all incident radiation is called as a grey body. Unlike blackbody, grey body emits less than total energy. Thus the total radiant emittance of grey body is given by formula (3.5),

$$W_g = \varepsilon\sigma T_2^{\,4} \tag{3.5}$$

where ε ($0<\varepsilon<1$) is emissivity.

CHAPTER 4

FUNDAMENTALS OF INFRARED IMAGING

4.1 Classification of Infrared

The classification of infrared, by application, is as follows[12]:

1. Near-infrared (NIR, IR-A DIN)

Its wavelength is from 0.75 to 1.4 µm (frequency is from 214 to 400 THz), and is defined by water absorption. Due to the low attenuation losses in silica glass, it is usually utilized in optical fiber communication. In this range of wavelengths, the enhanced image is very sensitive and can be easily captured for applications. Because of this, it is used in night vision devices, such as night vision goggles. DIN refers to the German Institute for Standardization - Deutsches Institut fur Normung.

2. Short-wavelength infrared (SWIR, IR-B DIN)

Its wavelength is from 1.4 to 3 µm (frequency is from 100 to 214 THz). The water absorption has significant increase at 1450 nanometers. From 1530 to 1560 nanometers, it is dominated mainly by spectrum of interest for long-distance telecommunication.

3. Mid-wavelength infrared (MWIR, IR-C DIN, MidIR. Also called intermediate infrared, IIR)

Its wavelength is from 3 to 8 µm (frequency is from 37-100 THz). In missile technology, 3-5µm-wavelength infrared is used to design the homing heads of passive IR 'heat seeking' missiles. This area is also known as thermal infrared.

4. Long-wavelength infrared (LWIR, IR-C DIN)

Its wavelength is from 8 to 15 µm (frequency is from 20-37 THz) . This range of wavelength is utilized in thermal imaging. The sensor in this range does not need other light or external heat source, such as the sun, moon or infrared lamp. It can obtain complete heat emissions of passive images. Forward-looking infrared (FLIR) system uses the spectrum in this range of wavelengths. Sometimes it can also be called as far infrared. Only one wavelength is suitable for firefighting applications. It is the long wave infrared.

5. Far infrared (FIR)

Its wavelength is from 15 to 1000 μm (frequency is from 0.3 to 20 THz). It is also called as far-infrared laser. The applications of FIR laser are in terahertz spectroscopy and terahertz imaging in fusion plasma physics diagnostics. FIR laser can also detect explosives and chemical warfare agents.

4.2 Infrared Imaging of Materials

All objects at temperature higher than absolute zero produce thermal radiation. When the temperature of matter is higher than absolute zero, the kinetic energy of the atoms or molecules will change because of inter-atomic collisions. These changes cause charge acceleration and/or dipole oscillation which emits electromagnetic radiation. The properties of infrared radiation have been described in chapter 3.

Compared with visible light, the infrared camera detects infrared (IR) radiation to yield infrared images. Here are some examples of comparisons of images in the visible range of wavelengths with those in the infrared.

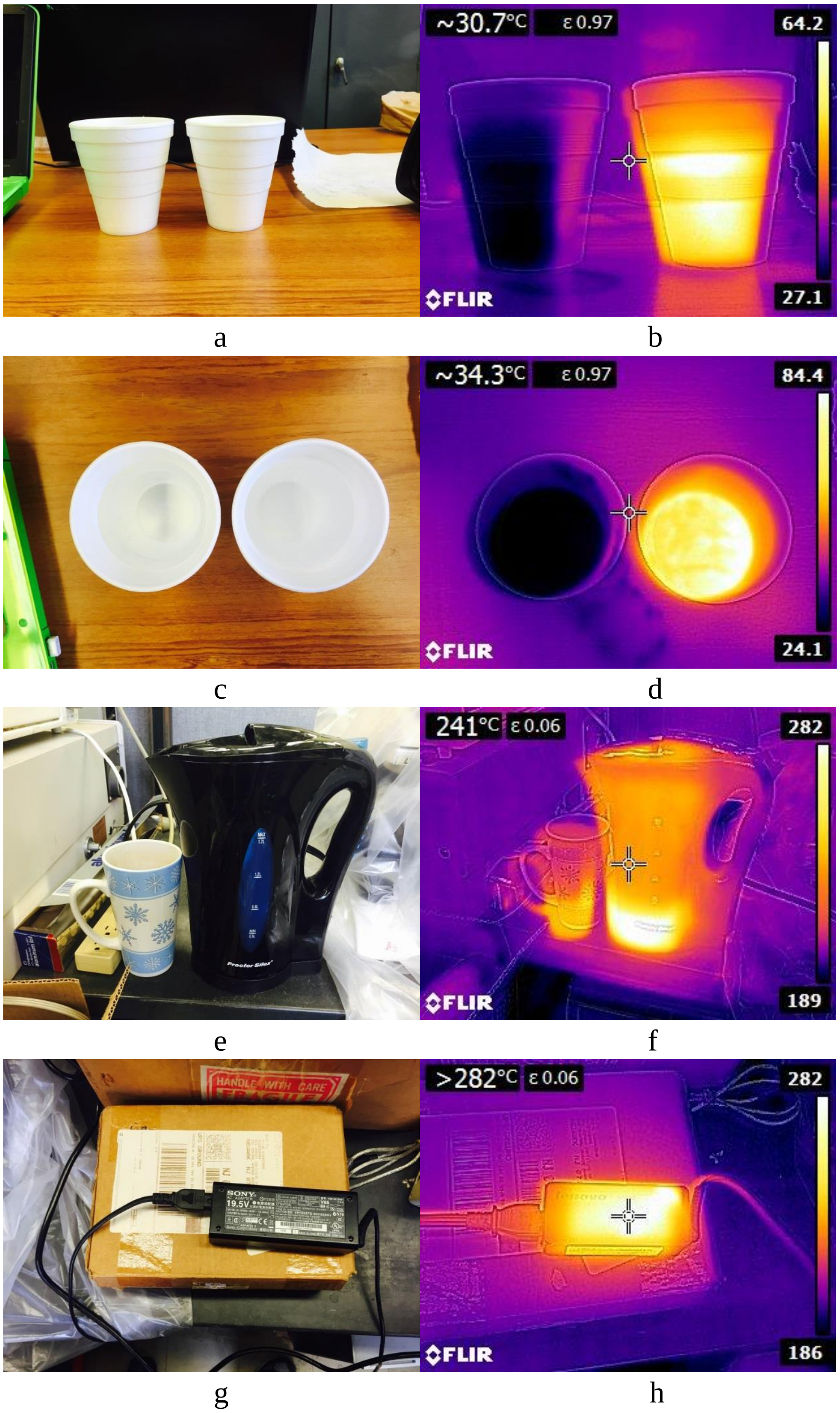


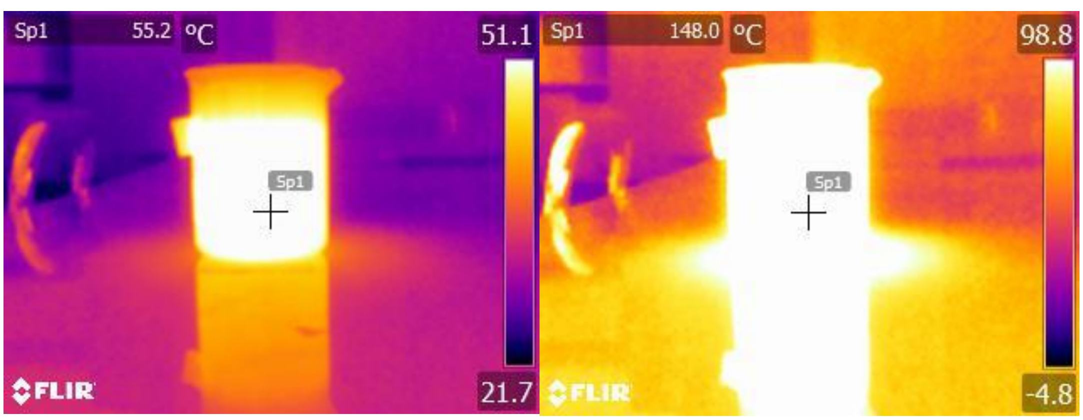
Figure 4.1 (a) Visible image of cups containing cold water and hot water. (b) Infrared image of (a). (c) Visible image of top-view of cups in picture (a). (d) Infrared image of (c). (e) Visible image of electric kettle. (f) Infrared image of (e). (g) Visible image of computer charger. (h) Infrared image of (g).

4.3 Emissivity

The emissivity of the surface of a material is its effectiveness in emitting energy as thermal radiation. It is the most important property to be considered for infrared imaging. Quantitatively, emissivity is the ratio of the thermal radiation from a surface to the radiation from an ideal black surface at the same temperature as given by the Stefan–Boltzmann law. This ratio varies from 0 to 1.

4.3.1 Emissivity and Infrared Imaging

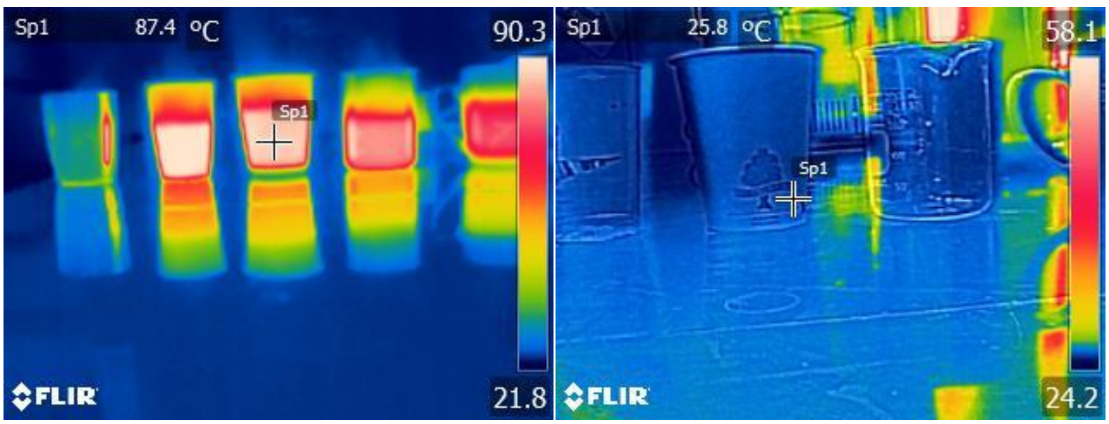
The emissivity, ε, is the most important object parameter to be set by FTIR-E6 camera. By setting different emissivity, we get different infrared images.



a b

Figure 4.2 (a) Infrared image of hot water in a cup - emissivity = 0.80.
(b) Infrared image of hot water in a cup - emissivity = 0.20.

Different surface roughness or types of materials have different emissivity. It is the effectiveness of emitting energy as thermal radiation. Or we can measure how much radiation is emitted from an object by comparing to that from a blackbody at the same temperature. Near room temperature, the radiation is not visible to human eyes because it is infrared. An object at high temperature has strong thermal radiation and depending on the nature of the object, it is visible, indirectly, to the human eye. For example, boiling can be seen as convection currents in liquids.



a b

Figure 4.3 (a) Infrared image of hot water in cups of various materials. (b) Infrared image of water in cups of various materials at room temperature.

4.3.2 Common Emissivity

The range of emissivity is from 0 to 1. Emissivity of a highly polished (mirror) surface is below 0.1, while oxidized and painted surface has higher emissivity. Moreover, the emissivity of rough surface, like some stones, is greater than 0.9. Human skin has an emissivity of 0.97 to 0.98.

Emissivity measurements for many surfaces are compiled in many handbooks and texts. Some of these are listed in Table 4.1[13, 14].

Table 4.1 Common Emissivity Parameters

Surface Material	Emissivity Coefficient	Surface Material	Emissivity Coefficient
Alloy 24ST Polished	0.09	Asphalt	0.93
Alumina, Flame sprayed	0.8	Basalt	0.72
Aluminum Commercial sheet	0.09	Beryllium	0.18
Aluminum Foil	0.04	Beryllium, Anodized	0.9
Aluminum Commercial Sheet	0.09	Bismuth, bright	0.34
Aluminum Heavily Oxidized	0.2 - 0.31	Black Body Matt	1.00
Aluminum Highly Polished	0.039 - 0.057	Black lacquer on iron	0.875
Aluminum Anodized	0.77	Black Parson Optical	0.95
Aluminum Rough	0.07	Black Silicone Paint	0.93
Aluminum paint	0.27 - 0.67	Black Epoxy Paint	0.89
Antimony, polished	0.28 - 0.31	Black Enamel Paint	0.80
Asbestos board	0.96	Brass Dull Plate	0.22
Asbestos paper	0.93 - 0.945	Brass Rolled Plate Natural Surface	0.06

Table 4.1 (Continued) Common Emissivity Parameters

Surface Material	Emissivity Coefficient	Surface Material	Emissivity Coefficient
Brass Polished	0.03	Coal	0.80
Brass Oxidized 600^{o}C	0.6	Concrete	0.85
Brick, red rough	0.93	Concrete, rough	0.94
Brick, fireclay	0.75	Concrete tiles	0.63
Cadmium	0.02	Cotton cloth	0.77
Carbon, not oxidized	0.81	Copper electroplated	0.03
Carbon filament	0.77	Copper heated and covered with thick oxide layer	0.78
Carbon pressed filled surface	0.98	Copper Polished	0.023 - 0.052
Cast Iron, newly turned	0.44	Copper Nickel Alloy, polished	0.059
Cast Iron, turned and heated	0.60 - 0.70	Glass smooth	0.92 - 0.94
Cement	0.54	Glass, pyrex	0.85 - 0.95
Chromium polished	0.058	Gold not polished	0.47
Clay	0.91	Gold polished	0.025

Table 4.1 (Continued) Common Emissivity Parameters

Surface Material	Emissivity Coefficient	Surface Material	Emissivity Coefficient
Granite	0.45	Magnesia	0.72
Gravel	0.28	Magnesite	0.38
Gypsum	0.85	Magnesium Oxide	0.20 - 0.55
Ice smooth	0.966	Magnesium Polished	0.07 - 0.13
Ice rough	0.985	Marble White	0.95
Inconel X Oxidized	0.71	Masonry Plastered	0.93
Iron polished	0.14 - 0.38	Mercury liquid	0.1
Iron, plate rusted red	0.61	Mild Steel	0.20 - 0.32
Iron, dark gray surface	0.31	Molybdenum polished	0.05 - 0.18
Iron, rough ingot	0.87 - 0.95	Mortar	0.87
Lampblack paint	0.96	Nickel, elctroplated	0.03
Lead pure unoxidized	0.057 - 0.075	Nickel, polished	0.072
Lead Oxidized	0.43	Nickel, oxidized	0.59 - 0.86
Limestone	0.90 - 0.93	Nichrome wire, bright	0.65 - 0.79
Lime wash	0.91	Oak, planed	0.89

Table 4.1 (Continued) Common Emissivity Parameters

Surface Material	**Emissivity Coefficient**	**Surface Material**	**Emissivity Coefficient**
Oil paints, all colors	0.92 - 0.96	Pyrex	0.92
Paper offset	0.55	PVC	0.91 - 0.93
Plaster	0.98	Quartz glass	0.93
Platinum, polished plate	0.054 - 0.104	Roofing paper	0.91
Pine	0.84	Rubber, foam	0.90
Plaster board	0.91	Rubber, hard glossy plate	0.94
Porcelain, glazed	0.92	Rubber, natural hard	0.91
Paint	0.96	Rubber, natural oft	0.86
Paper	0.93	Salt	0.34
Plaster, rough	0.91	Sand	0.76
Plastics	0.90 - 0.97	Sandstone	0.59
Polypropylene	0.97	Sapphire	0.48
Polytetrafluoroethylene (PTFE)	0.92	Sawdust	0.75
Porcelain glazed	0.93	Silica	0.79

Table 4.1 (Continued) Common Emissivity Parameters

Surface Material	**Emissivity Coefficient**	**Surface Material**	**Emissivity Coefficient**
Silicon Carbide	0.83 - 0.96	Tin unoxidized	0.04
Silver Polished	0.02 - 0.03	Titanium polished	0.19
Soil	0.90 - 0.95	Tungsten polished	0.04
Steel Oxidized	0.79	Tungsten aged filament	0.032 - 0.35
Steel Polished	0.07	Water	0.95 - 0.963
Stainless Steel, weathered	0.85	Wood Beech, planned	0.935
Stainless Steel, polished	0.075	Wood Oak, planned	0.885
Stainless Steel, type 301	0.54 - 0.63	Wood, Pine	0.95
Steel Galvanized Old	0.88	Wrought Iron	0.94
Steel Galvanized New	0.23	Zink Tarnished	0.25
Thoria	0.28	Zink polished	0.045
Tile	0.97		

Source: http://www.engineeringtoolbox.com/emissivity-coefficients-d_447.html

4.3.3 Measurement of Emissivity

The emissivity of materials of four cups that were used in this study is not listed in the above table. So we cannot use the values from Table 4.1. We need to find the emissivity of our samples. With the FLIR camera, utilized in these studies, it becomes easier. We use an object with known emissivity to measure its temperature. Keeping the test object at same temperature, we change the emissivity setting until reading the same temperature value. This is the ‘unknown’ emissivity of the material.

Quantitatively, emissivity is the ratio of the thermal radiation from a surface to the radiation from an ideal black surface at the same temperature as given by the Stefan–Boltzmann law[15].

We follow the procedure, as detailed below, in our measurements.

Step1: Determining reflected apparent temperature

We look for possible reflection sources and consider that the angle of incidence is equal to angle of reflectance. If the reflection source is a spot source, we have to modify the source by blocking it which is by using a piece of cardboard.
Measure the radiation intensity (it is equal to apparent temperature) from the reflecting source by using the following setting:
a. Emissivity = 1.0.
b. D_{obj}= 0.

Step 2: Determining the emissivity.

Following is the next step:

1. Select a place to put the sample.
2. Determine and set reflected apparent temperature in accordance with the previous procedure.
3. Put a piece of electrical tape with known high emissivity on the sample.
4. Heat the sample by at least 20 K above room temperature. Heating must be reasonably even.
5. Focus and auto-adjust the camera, and freeze the image.

6. Adjust LEVEL and SPAN for best image brightness and contrast.
7. Set emissivity to that of the tape (usually 0.97).
8. Measure the temperature of tape.
9. Note the temperature.
10. Move the measurement function to the sample surface.
11. Change the emissivity setting until we read the same temperature as the previous measurement.
12. Note the emissivity.

4.4 Applications of Infrared Imaging

One of the several applications of infrared imaging includes moisture detection or drying process. With the infrared thermography camera, we can monitor the damage to the walls/structure due to moisture (see Figure 4.4), which cannot be detected by visible camera or our eyes.

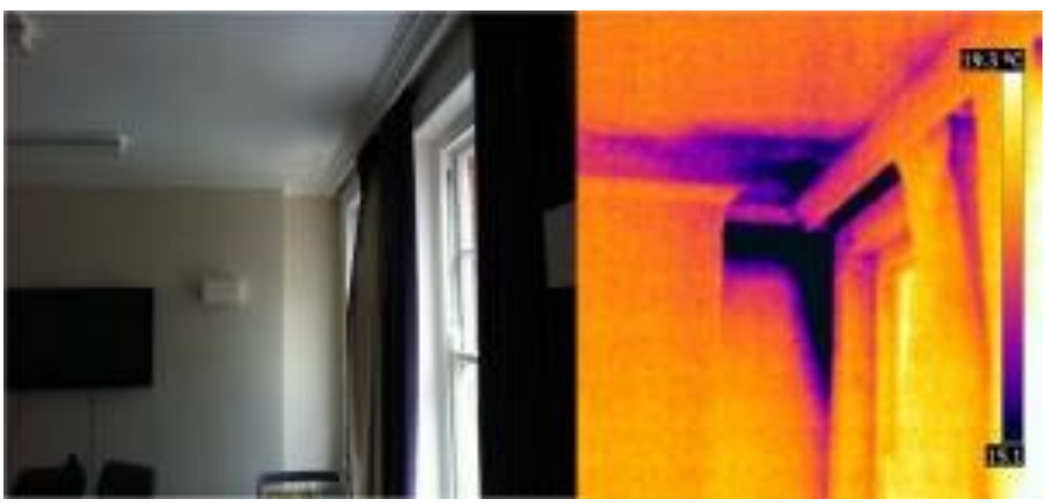


Figure 4.4 Infrared imaging of damage in wall due to moisture.

Source: http://waterdamage.co.uk/thermal-imaging-leak-detection.

Infrared imaging has other applications relating to the investigation of historic structures.[16] In particular, infrared imaging is a non-destructive technique to retain, restore or repair a variety of traditional-historical structures. For example, Stone consolidation is quite a risky conservation because stone structure is easy to be corroded.[17] These structures cannot be moved to detect corrosion. Nonetheless, it is necessary because decay and loose cohesion under the surface will destroy it. In this case, infrared thermography is an effective method to evaluate historical buildings and sites. Different situations will require different treatments. In some cases, it is necessary to measure the emissivity values of the materials to be investigated in a lab setting.

In addition, thermal imaging offers the significant advantage of two-dimensional temperature measurements in real time. With modern technology, a single image may contain several thousands of temperature points, recorded in a fraction of a second.

The human body is homeothermic. The inside of body is relatively stable in temperature, and the shell of the body (the surface tissues, mainly the skin) is in regulatory process and heat preservation. Human skin is a near-blackbody with an emissivity of 0.96–0.98. [18]

The measurement of human body temperature is a traditional skill to diagnose disease. It is almost as old as medicine. Commonly measured temperature includes oral temperature, rectal temperature and axillary temperature. The normal range of body temperature is close to 37 ℃.

Infrared images have been used in the diagnosis for more than 50 years. Many diseases can be displayed through the skin with infrared imaging. This method does not require medication or surgery. Although infrared imaging cannot accurately diagnose the disease, it can still be substantially judged combined with other methods or experience. In principle, thermal imaging can be applied in medicine either as a diagnostic test or as outcome measure for clinical trials.

It also has other applications in clinical practice such as inflammatory processes (joints, soft tissues), phlebology (vein thrombosis), vascular cancer and ischemia of the limbs.

From early times, doctors have used it to diagnose inflammatory diseases, such as pain, swelling, heat, redness and loss of function. When a joint has acute inflammation, doctors can feel the heat by touching. However, subtle changes in temperature on the surface are difficult to judge the inflammation better or worse. So it is very necessary to use infrared imaging as more accurate measurement of temperature.

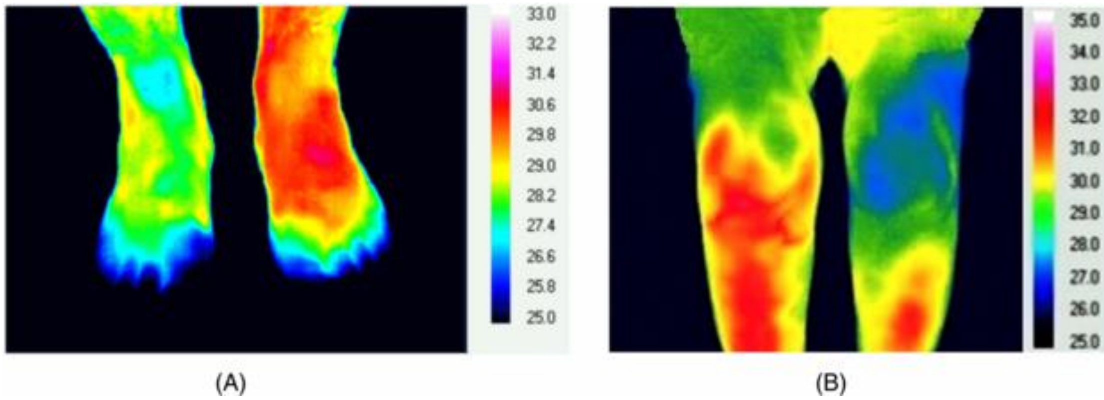


Figure 4.5 (A) Chronic inflammation of the forefoot following a sports injury; (B) Rheumatoid arthritis of one knee (left of the image).

Source: E F J Ring, K Ammer. Infrared thermal imaging in medicine. Physiological Measurement, 33, 3.

4.5 Advantages of Infrared Imaging

Infrared Imaging has a several advantages. These include the following:

1. Safety - Avoid catastrophic failure or injury.

2. Greater asset reliability - Reduces unscheduled outages.

3. Increased revenue - More uptime, revenue is maximized.

4. Reduced outage costs - Planned maintenance saves.

5. More efficient inspections - Just looking for heat.

6. Improved and less expensive maintenance.

7. Reduced spare parts inventory - Fewer spares.

8. Reduced operational costs.

CHAPTER 5

MICROBOLOMETER- BASED FLIR CAMERA

5.1 History of Thermal Imaging

Thermal imaging technology was originally developed for military applications. From 1950 to 1960, single element detectors were used for line images. It took an hour to produce an image. In 1970, Philips and English Electronic Valve (EEV) developed the pyro-electric tube. This is the first navy thermal imager. Legacy Imager (EEV) was developed with this technology. It is cumbersome and is no longer manufactured. In this device, the user cannot restart or clear lens. Pyroelectric Vidicon used tube technology and was produced from 1982 to 1998. This type of sensor has low sensitivity. When pointed to a fire, it forms a whiteout which is unable to reset. Furthermore, when subjected to heat, this sensor could be damaged permanently. It still could not resolve movement or direction of thermal energy. Barium Strontium Titanate (BST) based detectors are being produced since 1998 (to present) by Raytheon. As current Navy thermal imagers (ISG-K90 Talisman), it has already overcome the above two problems. In the late 1980's microbolometer technology was developed. This type of sensor has been in production from 2000 to present[19].

5.2 Microbolometer

In a thermal camera, there is a detector called the microbolometer which is a specific type of bolometer. Infrared camera uses this to detect infrared radiation. When the wavelength of infrared radiation is between 7.5-14 µm, this radiation can heat the material and pass through it. This changes its electrical resistance, which can be measured and creates an image resulting in temperature measurements.

Unlike other thermal sensors, microbolometer does not require cooling. As an uncooled infrared detector, it helps thermal sensors to get rid of exotic and expensive cooling equipment including liquid nitrogen coolers or Stirling cycle coolers. Early thermal cameras have been more expensive to operate and more difficult to move due to these cooling equipment. Moreover, thermal cameras save more than 10 minutes before being usable without cooling down.

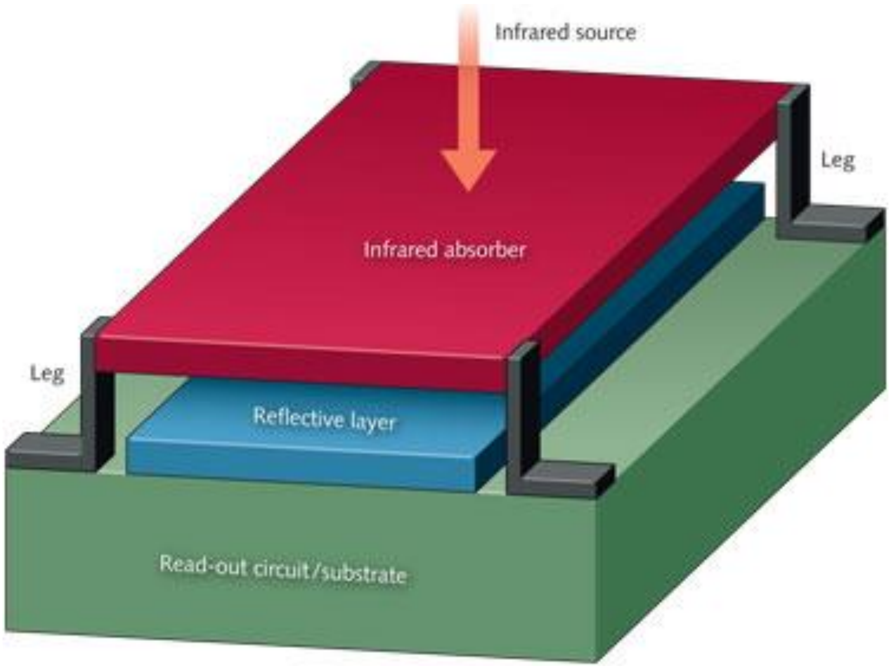


Figure 5.1 One pixel in a microbolometer array. An infrared-absorbing surface is elevated above the substrate and thermally isolated from the adjacent pixels. Low mass increases the temperature change from heat absorption. Read-out circuits typically are in the base layer, which may be coated with a reflective material to reflect transmitted IR and increase absorption of the pixel.

Source: Jeff Hecht. (Contributing Editor, Photonic Frontiers). Photonic Frontiers: Room-temperature IR imaging: Microbolometer arrays enable uncooled infrared camera. Laser Focus World. April 2012.

There are two types of IR-absorbing materials for microbolometers. Pyroelectric or ferroelectric crystals generate electrical signals which will be stronger with increasing temperature. It is caused by infrared absorption. The most common material now is using barium-strontium titanate. Today, the semiconductor amorphous silicon and vanadium oxide (commonly abbreviated as VOx) play important roles[20] in infrared imaging technology.

Several factors affect the microbolometer performance. Different sensitivity depends on different resistance or other electrical signal changes with temperature, which depends on the absorbing material. Besides, the other factor is pixel response time. The absorber should collect heat quickly and keep it long enough to be able to measure. After this, heat should dissipate before the next frame. Also, the read-out integrated circuit (ROIC) can influence the response time and performance. The ROIC is used to collect the temperature data of all pixels for each frame.

5.3 Infrared Camera

For an infrared camera, there are several main parts of the camera structure such as lens, detector, converter, digital processor and so on. FLIR-E6 was used in our experiments. This camera belongs to the FLIR-EX series. The type of detector of FLIR-E6 is a microbolometer. The photograph of FLIR-E6 camera is presented in Figure 5.2.

Figure 5.2 FLIR-E6 camera.

5.4 Operation of a Thermal Imager

Most cameras, in daily use, are visual cameras. When we take a picture, a photon, as the carrier, passes through the photographic lens and split-second information of light about this object transfers to the photosensitive material in the way of energy. Eventually, it becomes a visual image with refraction or reflection, which focuses on the image plane accurately.

Compared with visual camera, infrared camera works on a different principle. Infrared light, which is emitted by all the objects on the screen, is focused through a special lens. Then, the infrared detector scans and focuses light and creates electrical impulses. These impulses are sent to the digital processor which can convert these signals into a variety of color depending on the strength of the infrared emission.

CHAPTER 6

IMAGING STUDIES

6.1 Phase Transition

Phase transition is a thermodynamic transformation from one state to another by heat transfer. It is most commonly used to describe the conversion between solid, liquid and gaseous phase of material. Phase transition occurs due to external conditions for conversion from one phase to the other.

6.2 Heat Transfer

Heat transfer is the exchange of thermal energy between physical systems by means of electromagnetic waves. These exchanges can occur when the bodies are separated from one another by vacuum or by a transparent or a semi-transparent medium. It is a path function. Heat always transfers from the hotter to colder object. In order to evaluate these radiative heat exchanges, it is necessary to know how opaque and semi-transparent bodies emit, absorb and transmit radiation as a function of their nature, relative position and temperature[21]. There are three main methods to transfer heat energy including conduction, convection and radiation.

Conduction usually needs at least one solid as its medium. This energy transfer needs objects that are in physical contact. The property of a material to describe it is thermal conductivity. In our experiment, this heat transfer occurs from hot water to cups and then to table. Convection usually occurs between the object and the environment surrounding it. In our experiment, this heat transfer occurs from cups to environment. The third one is radiation. This transfer of energy is by the emission of electromagnetic radiation. In our experiment, this heat transfer occurs from cups to FLIR camera. Moreover, in transient heat transfer, one more parameter must be considered which is the heat capacity of the material. It has influence on the rate of temperature change.

Radiation is different from conduction and convection. It does not need a medium. Conduction and convection are linearly proportional to temperature difference. Radiation from a surface is proportional to the fourth power of absolute temperature. Heat exchange between two objects involves complex relationships of geometry, emissivity and surrounding objects.

6.3 Measurement of Temperature

Temperature is a measurement of hotness and/or coldness. Many devices have been invented to accurately measure temperature. It all started with the establishment of a temperature scale. This scale transformed the measurement of temperature into meaningful numbers. The most commonly used temperature scales are Fahrenheit and Celsius.

Recently, the methods of measuring the temperature are as many as dozens. According to the different laws of physics and different selected physical quantity, measurement methods can be classified into several groups.

One of the most common devices for measuring temperature is the glass thermometer. It consists of a glass tube and a glass bead, which is filled with mercury. The increasing temperature causes the fluid to expand. The volume of the fluid is as the temperature scales. So we can read the temperature simply by reading the number corresponding to the fluid in the thermometer.

Other important devices for measuring the temperature include: thermocouples, thermistors, resistance temperature detector (RTD), pyrometer, Langmuir probes (for electron temperature of a plasma), infrared and so on.

There is no certain absolute way to defeat infrared. Only a few techniques can make detection more difficult.

6.4 Important Factors for Temperature Measurements

There are several important factors for temperature measurement with infrared camera. These factors include the following: surface emissivity, surface thermal reflectivity, background temperature, thermal capacitance, angle of view, system load, distance of measurement, camera settings, heat transfer and solar and wind conditions. Surface emissivity is the property of the object. It can be found in emissivity tables in the literature. Or it can be measured by following the procedure as described earlier. Others factors can be controlled by setting the environment for the FLIR camera.

6.5 Radiation Transfer Formula

The subject of infrared radiation and the related technique of thermography are still new. They are used in infrared camera, and in this section, the theory of thermography will be described.

When viewing an object, the camera receives radiation not only from the object itself. It also collects radiation from the surroundings reflected via the object surface. Both these contributions to radiation become attenuated to some extent by the atmosphere in the measurement path. A third contribution to the radiation is from the atmosphere itself.

From Kirchhoff's law: emissivity ($\in$) = absorptivity (a).

According to equation (2.7), using emissivity instead of absorptivity.

$$\rho + \in + \tau = 1 \tag{6.1}$$

Most materials are opaque rather than transparent. For opaque object, transmissivity τ is zero, which means,

$$\rho = 1 - \in \tag{6.2}$$

Accepting the description above, we can use Figure 5.1 to derive a formula for the calculation of the object temperature.

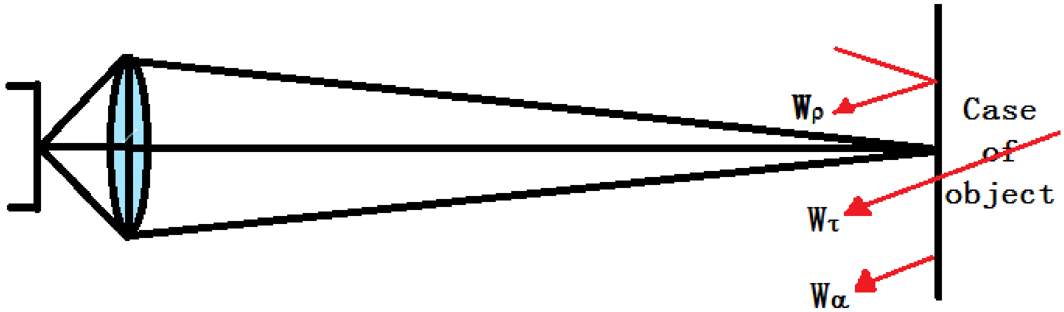


Figure 6.1 The power of reflectivity (ρ), absorptivity (a) and transmissivity (τ).

Assume that the power of received radiation is W_{Total} from a blackbody source of temperature T_B . The power of emissivity, reflectivity and transmissivity are $W_\in$, W_ρ and W_τ, respectively. T_T is the measured temperature. We can write these as follows:

$$\begin{aligned} W_{Total} &= W_\in + W_\rho + W_\tau \\ &= \in T_T^4 + \rho T_B^4 + 0 \end{aligned} \tag{6.3}$$

Accepting equation 6.3,

$$W_{Total} = \in T_T^4 + (1 - \in) T_B^4 \tag{6.4}$$

This description of the measurement situation, as illustrated in the figure above, is so far a fairly true description of the real conditions. What has been neglected, for instance, could be scattering of sun light in the atmosphere or stray radiation from intense radiation sources outside the field of view.

This is the general measurement formula used in all the FLIR Systems thermographic equipment.

CHAPTER 7

RESULTS AND DISCUSSION

7.1 Instrumentation

In our experiments, the instrumentation and supplies included the following: FLIR camera, electrical tape, four cups (including polystyrene cup, paper cup, stainless steel cup and ceramic mug), hot water, ice, metal, ruler, retort stand, thermometer, a bottle of red wine, a bottle of white wine and a styrofoam container.

Figure 7.1 The normal/visible image of four cups (including polystyrene cup, paper cup, stainless steel cup and ceramic mug).

7.2 Experiment

The following is the procedure for our experiments:

1. Prepare experimental setup.

   Put electrical tape on the cups.
   Fix FLIR camera with vertical stand with a cup in front of it. The distance between camera and cup is 30 cm.
   Initially, the FLIR camera focuses on the electrical tape.
   With the lights turned off.

2. Measure emissivity of cups

   Pour hot water into cup. Set emissivity = 0.97 to observe the temperature of electrical tape (spot) and then move the measurement function to the cup surface immediately. Change emissivity setting of camera as soon as possible until it is same with previous temperature. Write down the emissivity. Measure emissivity of other cups by following the above procedure.

3. Pour hot water into cups and capture images

   Pour hot water into cups and observe the shape and color changing in IR images. Capture images every 2 minutes until water temperature is about 20 degree above room temperature.

4. Put ice into cups

   Put ice into cups and observe the shape and color change in IR images. Acquire images every 2 minutes until most ice melts.

5. Put metal into cups

   Put a metal specimen into cups and observe if we can detect the shape through the cups or not.

6. Put finger into cups

   Put one finger into cups and observe if we can detect the shape through cups or not.

7.3 Results of Emissivity

We use the infrared camera to measure emissivity of four cups with decreasing temperature. Depending on the data, we prepare the chart of emissivity and temperature and analyze the variation.

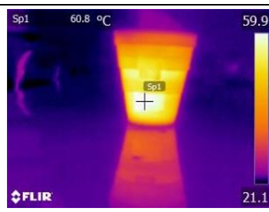
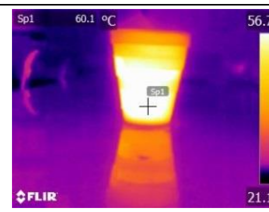
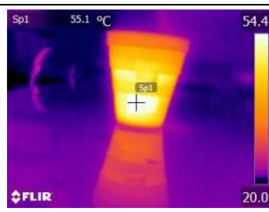
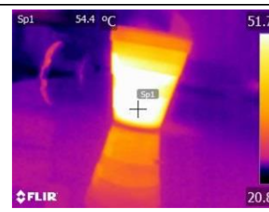
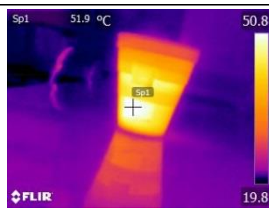
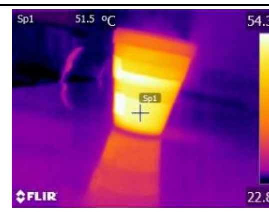
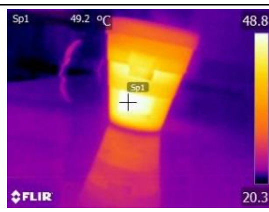
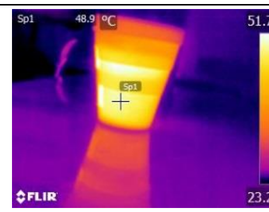
Groups A	Infrared image of electrical tape	Emissivity ε Temperature T/℃	Infrared image of polystyrene cup	Emissivity ε Temperature T/℃
1		0.97 60.8		0.81 60.1
2		0.97 55.1		0.81 54.4
3		0.97 51.9		0.85 51.5
4		0.97 49.2		0.87 48.9
5		0.97 47.2		0.85 47.1
6		0.97 46.5		0.84 45.9

Figure 7.2 A Groups A1-A6 show infrared image of polystyrene cup over time. We acquire two images at same temperature to measure emissivity of polystyrene cup at this temperature.

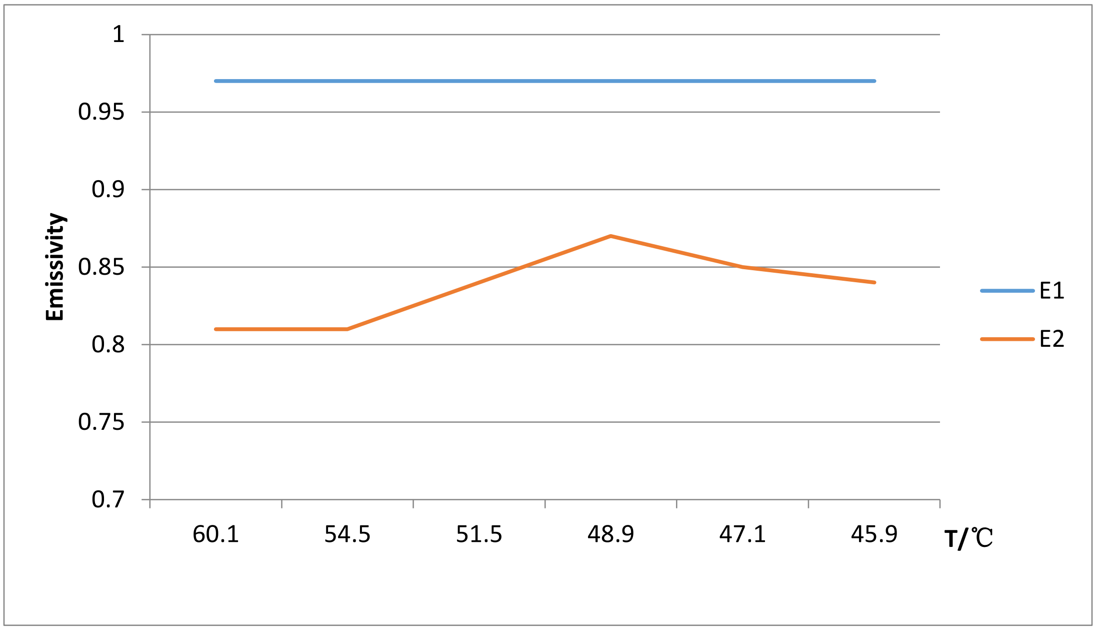


Chart 7.1 E1 is the emissivity of electrical tape with decreasing temperature. E2 is the emissivity of polystyrene cup with decreasing temperature.

With decreasing temperature, the emissivity of polystyrene cup is initially increasing and then decreasing. Chart 7.1 reveals that the variation is in a small range of temperature. The temperature has less influence on emissivity.

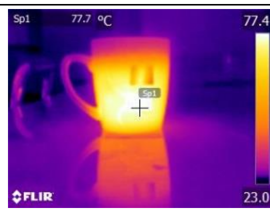
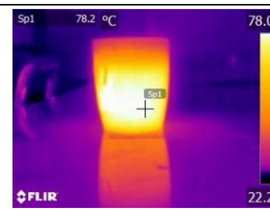
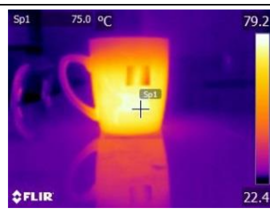
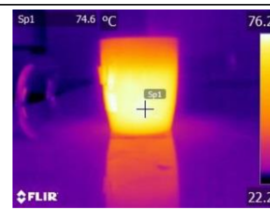
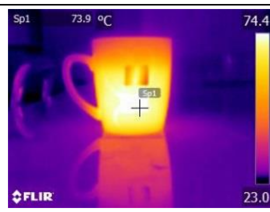
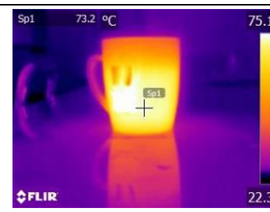
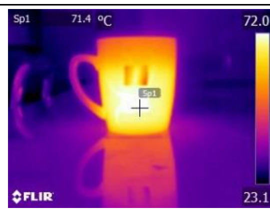
Groups B	Infrared image of electrical tape	Emissivity ε Temperature T/℃	Infrared image of ceramic mug	Emissivity ε Temperature T/℃
1		0.97 77.7		0.91 78.2
2		0.97 75.0		0.94 74.6
3		0.97 73.9		0.92 73.2
4		0.97 71.8		0.93 71.4
5		0.97 70.7		0.92 70.1
6		0.97 68.9		0.93 68.2

Figure 7.2 B Groups B1-B14 show infrared image of ceramic mug over time. We acquire two images at same temperature to measure emissivity of ceramic mug at this temperature.

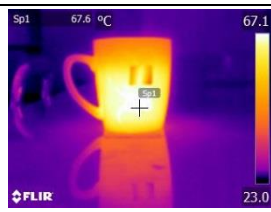
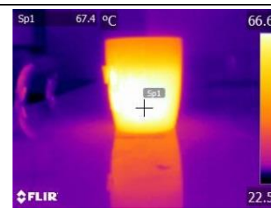
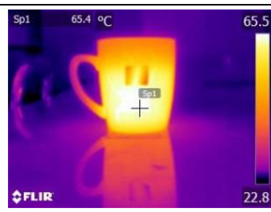
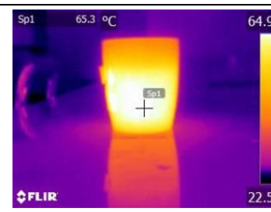
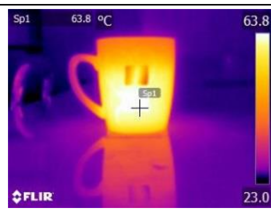
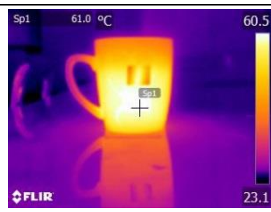
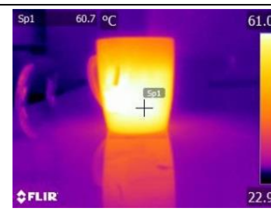
Groups B	Infrared image of electrical tape	Emissivity ε Temperature T/℃	Infrared image of ceramic mug	Emissivity ε Temperature T/℃
7		0.97 67.6		0.93 67.4
8		0.97 65.4		0.94 65.3
9		0.97 63.8		0.94 63.5
10		0.97 61.0		0.93 60.7
11		0.97 57.1		0.94 56.8
12		0.97 54.7		0.94 54.2

Figure 7.2 B (Continued) Groups B1-B14 show infrared image of ceramic mug over time. We acquire two images at same temperature to measure emissivity of ceramic mug at this temperature.

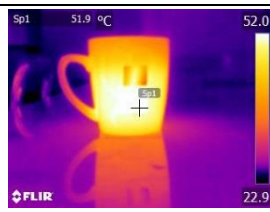
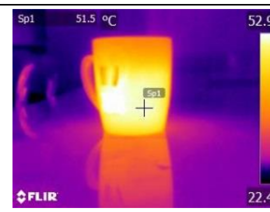
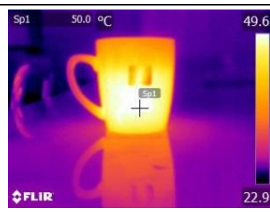
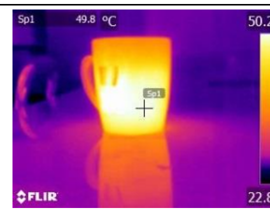
Groups B	Infrared image of electrical tape	Emissivity ε Temperature T/℃	Infrared image of ceramic mug	Emissivity ε Temperature T/℃
13		0.97 51.9		0.95 51.5
14		0.97 50.0		0.94 49.8

Figure 7.2 B (Continued) Groups B1-B14 show infrared image of ceramic mug over time. We acquire two images at same temperature to measure emissivity of ceramic mug at this temperature.

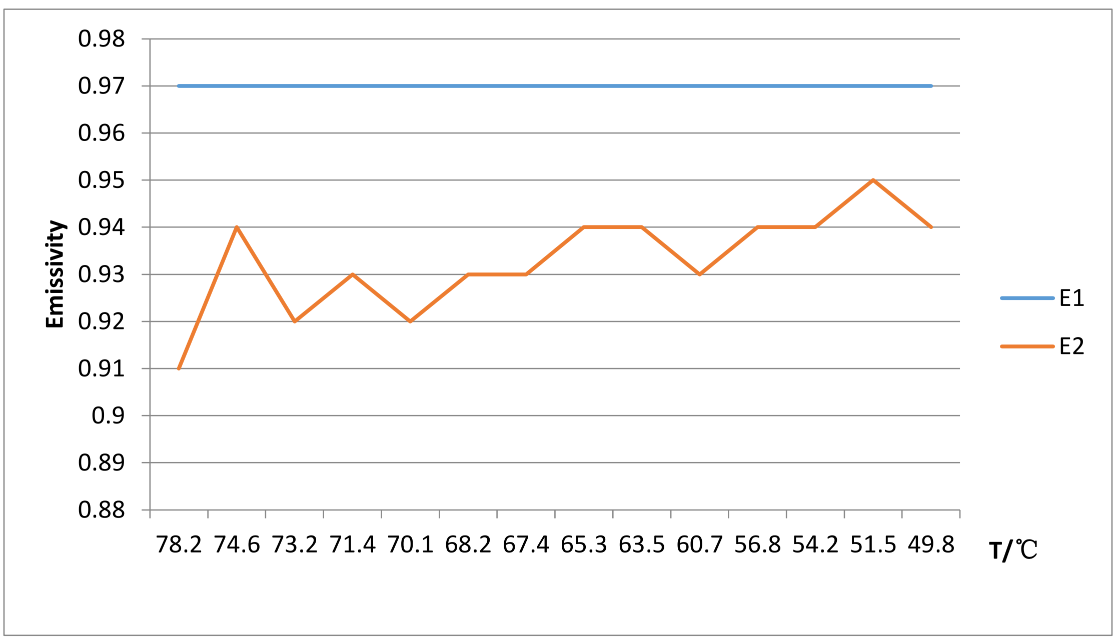


Chart 7.2 E1 is the emissivity of electrical tape with decreasing temperature. E2 is the emissivity of ceramic cup with decreasing temperature.

From Chart 7.2, we find that the emissivity has a tendency to increase, although it is not a straight line. With increasing temperature, the emissivity of ceramic cup has an increasing tendency.

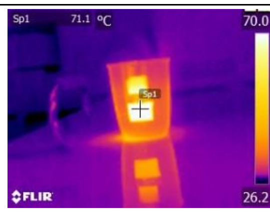
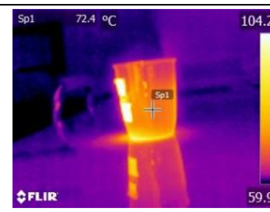
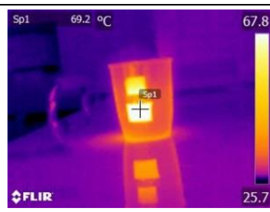
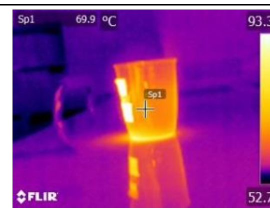
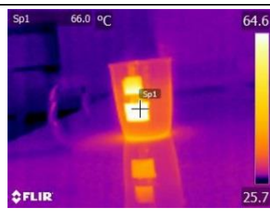
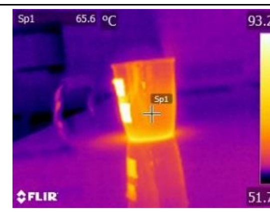
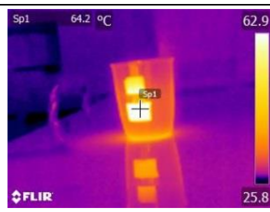
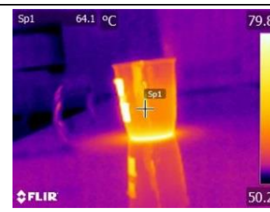
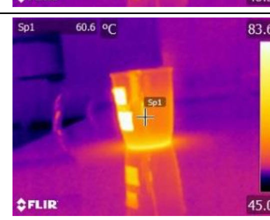
Groups C	Infrared image of electrical tape	Emissivity ε Temperature T/℃	Infrared image of stainless steel cup	Emissivity ε Temperature T/℃
1		0.97 71.1		0.37 72.4
2		0.97 69.2		0.41 69.9
3		0.97 66.0		0.42 65.6
4		0.97 64.2		0.45 64.1
5		0.97 62.5		0.47 61.8
6		0.97 60.1		0.47 60.6

Figure 7.2 C Groups C1-C17 show infrared image of stainless steel cup over time. We acquire two images at same temperature to measure emissivity of stainless steel cup at this temperature.

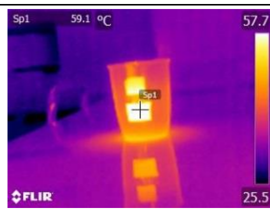
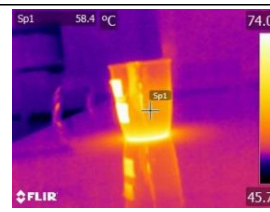
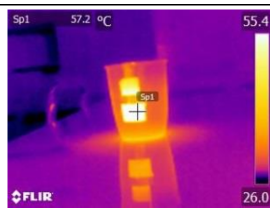
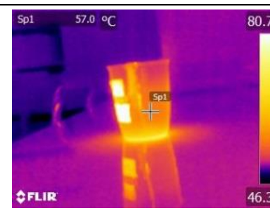
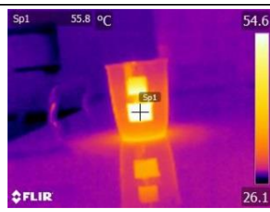
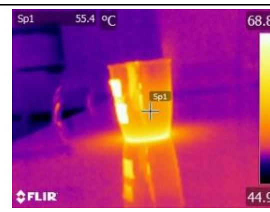
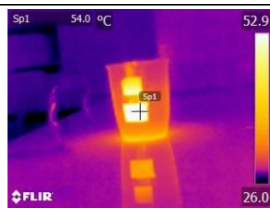
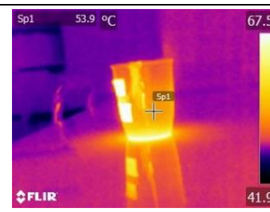
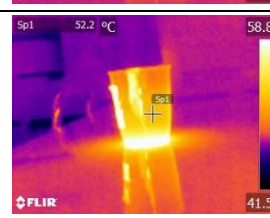
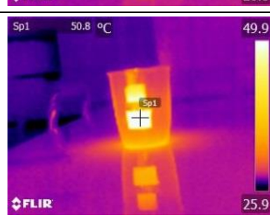
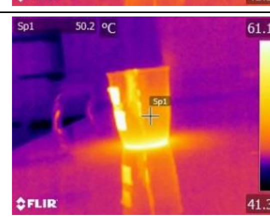
Groups C	Infrared image of electrical tape	Emissivity ε Temperature T/℃	Infrared image of stainless steel cup	Emissivity ε Temperature T/℃
7		0.97 59.1		0.46 58.4
8		0.97 57.2		0.48 57.0
9		0.97 55.8		0.49 55.4
10		0.97 54.0		0.50 53.9
11		0.97 52.5		0.52 52.2
12		0.97 50.8		0.54 50.2

Figure 7.2 C (Continued) Groups C1-C17 show infrared image of stainless steel cup over time. We acquire two images at same temperature to measure emissivity of stainless steel cup at this temperature.

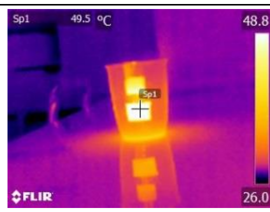
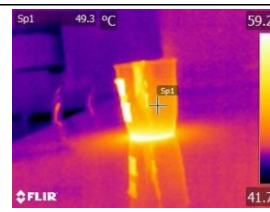
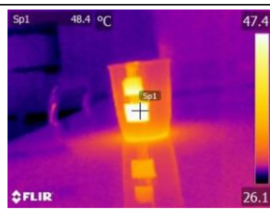
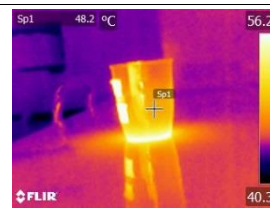
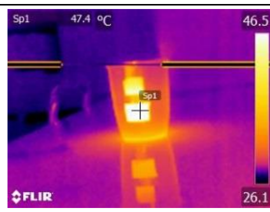
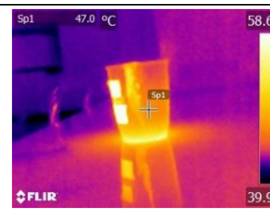
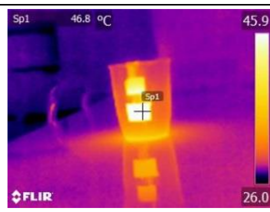
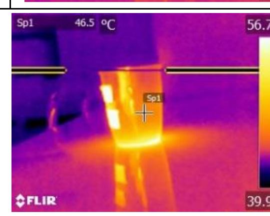
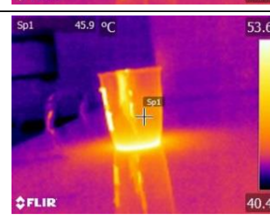
Groups C	Infrared image of electrical tape	Emissivity ε Temperature T/℃	Infrared image of stainless steel cup	Emissivity ε Temperature T/℃
13		0.97 49.5		0.55 49.3
14		0.97 48.4		0.56 48.2
15		0.97 47.4		0.58 47.0
16		0.97 46.8		0.58 46.5
17		0.97 46.0		0.59 45.9

Figure 7.2 C (Continued) Groups C1-C17 show the infrared image of stainless steel cup over time. We acquire two images at same temperature to measure emissivity of stainless steel cup at this temperature.

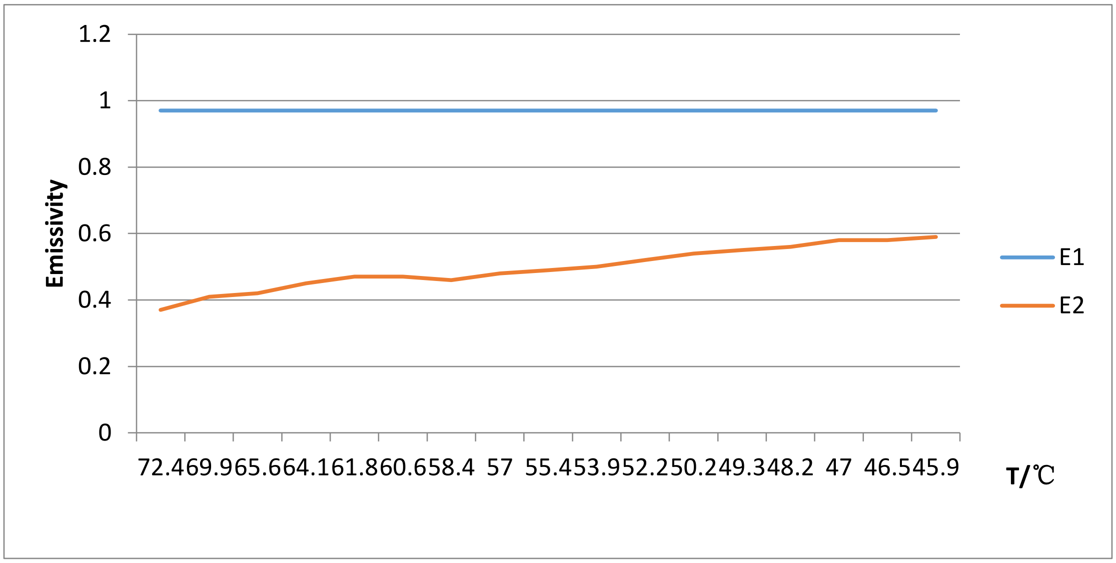


Chart 7.3 E1 is the emissivity of electrical tape with decreasing temperature. E2 is the emissivity of stainless steel cup with decreasing temperature.

Chart 7.3 reveals that the emissivity of stainless steel cup is increasing with decreasing temperature. It has significant increase from 0.4 to 0.6. Therefore, the temperature has more effect on emissivity of stainless steel.

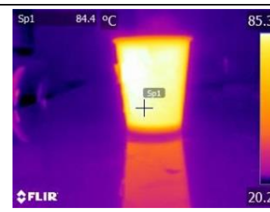
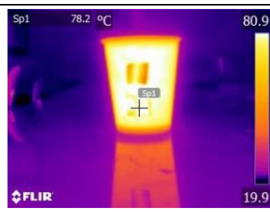
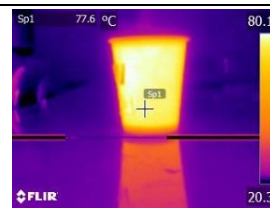
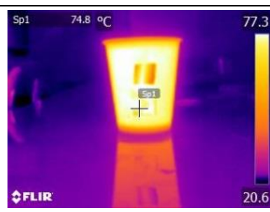
Groups D	Infrared image of electrical tape	Emissivity ε Temperature T/℃	Infrared image of paper cup	Emissivity ε Temperature T/℃
1		0.97 84.8		0.98 84.3
2		0.97 80.0		0.99 79.8
3		0.97 78.2		1.00 77.6
4		0.97 74.8		0.99 74.5
5		0.97 72.5		0.99 72.3
6		0.97 69.0		1.00 68.6

Figure 7.2 D Groups D1-D13 show infrared image of paper cup over time. We acquire two images at same temperature to measure emissivity of paper cup at this temperature.

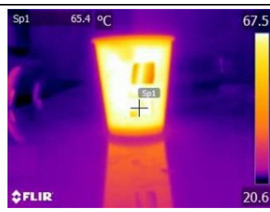
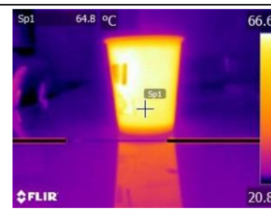
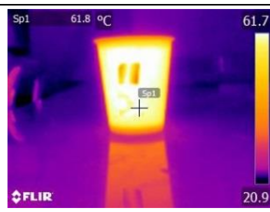
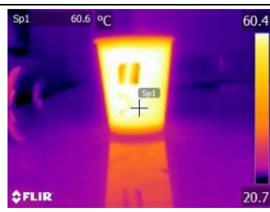
Groups D	Infrared image of electrical tape	Emissivity ε Temperature T/℃	Infrared image of paper cup	Emissivity ε Temperature T/℃
7		0.97 65.4		1.00 64.8
8		0.97 62.9		0.97 62.3
9		0.97 61.8		0.96 61.9
10		0.97 60.6		0.97 59.3
11		0.97 54.7		0.95 54.6
12		0.97 51.5		0.95 51.3

Figure 7.2 D (Continued) Groups D1-D13 show infrared image of paper cup over time. We acquire two images at same temperature to measure emissivity of paper cup at this temperature.

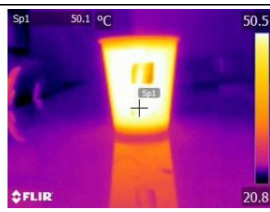
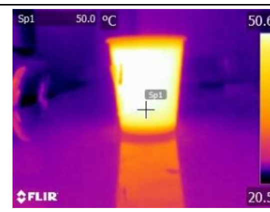
Groups D	**Infrared image of electrical tape**	**Emissivity ε Temperature T/℃**	**Infrared image of paper cup**	**Emissivity ε Temperature T/℃**
13		0.97 50.1		0.95 50.0

Figure 7.2 D (Continued) Groups D1-D13 show infrared image of paper cup over time. We acquire two images at same temperature to measure emissivity of paper cup at this temperature.

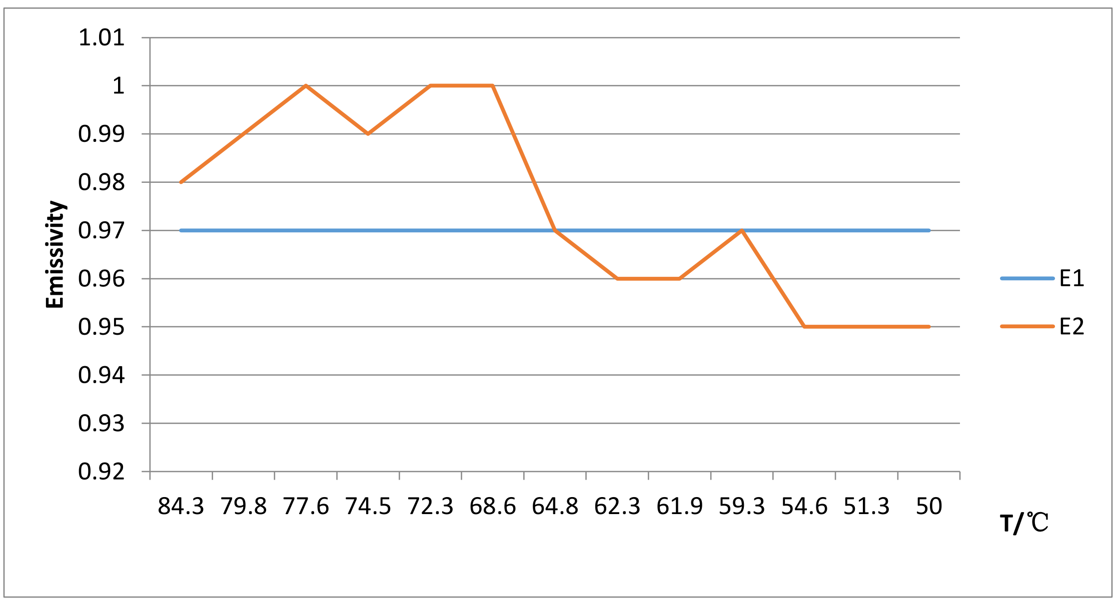


Chart 7.4 E1 is the emissivity of electrical tape with decreasing temperature. E2 is the emissivity of paper cup with decreasing temperature.

From Chart 7.4, the emissivity of paper cup has a decreasing tendency with decreasing temperature. It is the only one that shows the decreasing tendency amongst the four cups considered in this study. However, it is not proportional to temperature.

7.4 Ice in Cups

We acquired a series of infrared images of ice melting in four cups every 6 minutes. In our experiments, we can detect the color and shape depending on the temperature of ice from these infrared images.

7.4.1 Ice in Polystyrene Cup.

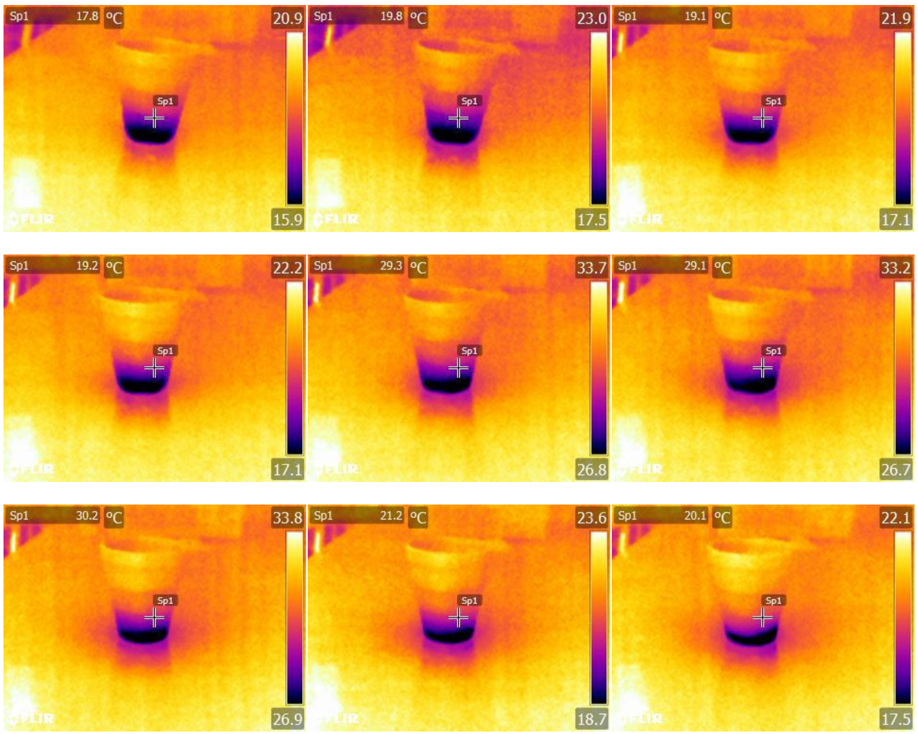


Figure 7.3 Infrared images of ice melting in polystyrene cup.

7.4.2 Ice in Ceramic Cup

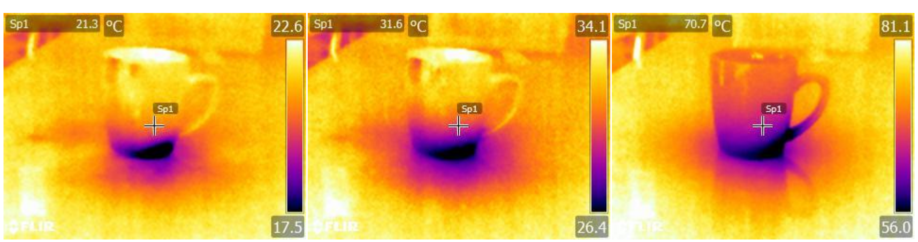


Figure 7.4 Infrared images of ice melting in ceramic cup.

7.4.3 Ice in Stainless Steel Cup

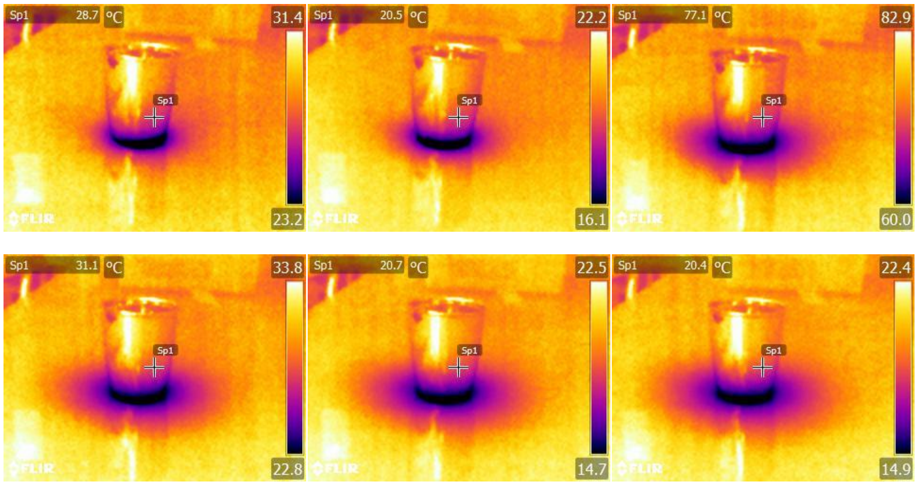


Figure 7.5 Infrared images of ice melting in stainless steel cup.

7.4.4 Ice in Paper Cup

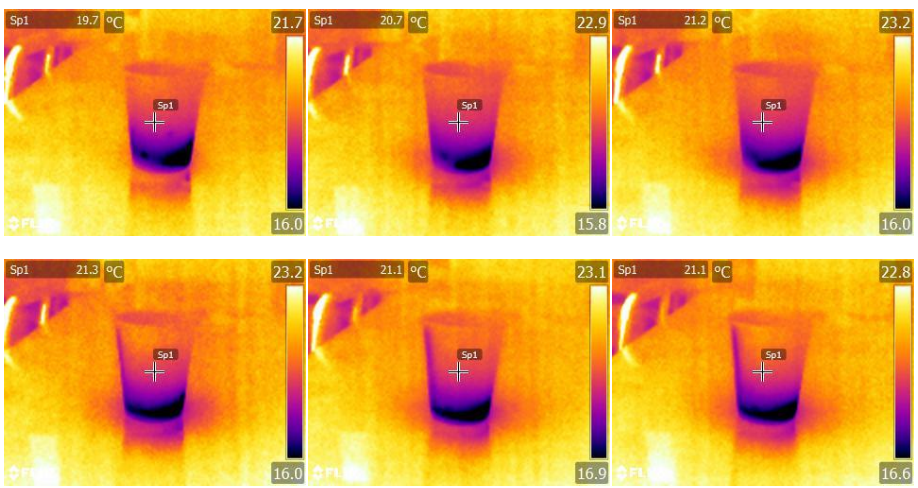


Figure 7.6 Infrared images of ice melting in paper cup.

7.5 Example - Finger in Cups

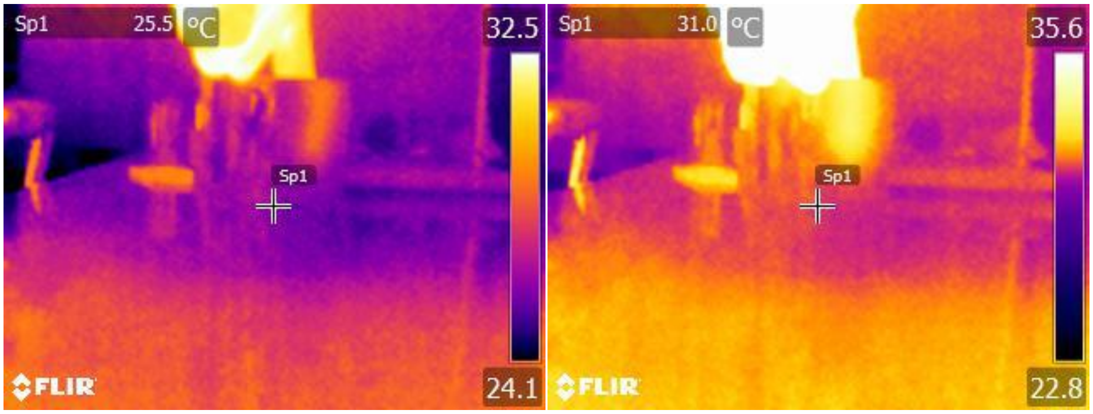


Figure 7.7 With changing emissivity from 1.0 to 0.8, the infrared images of finger in the cup.

We find that the finger cannot be detected at different emissivities. With emissivity set at one value, infrared images of four cups with finger inside.

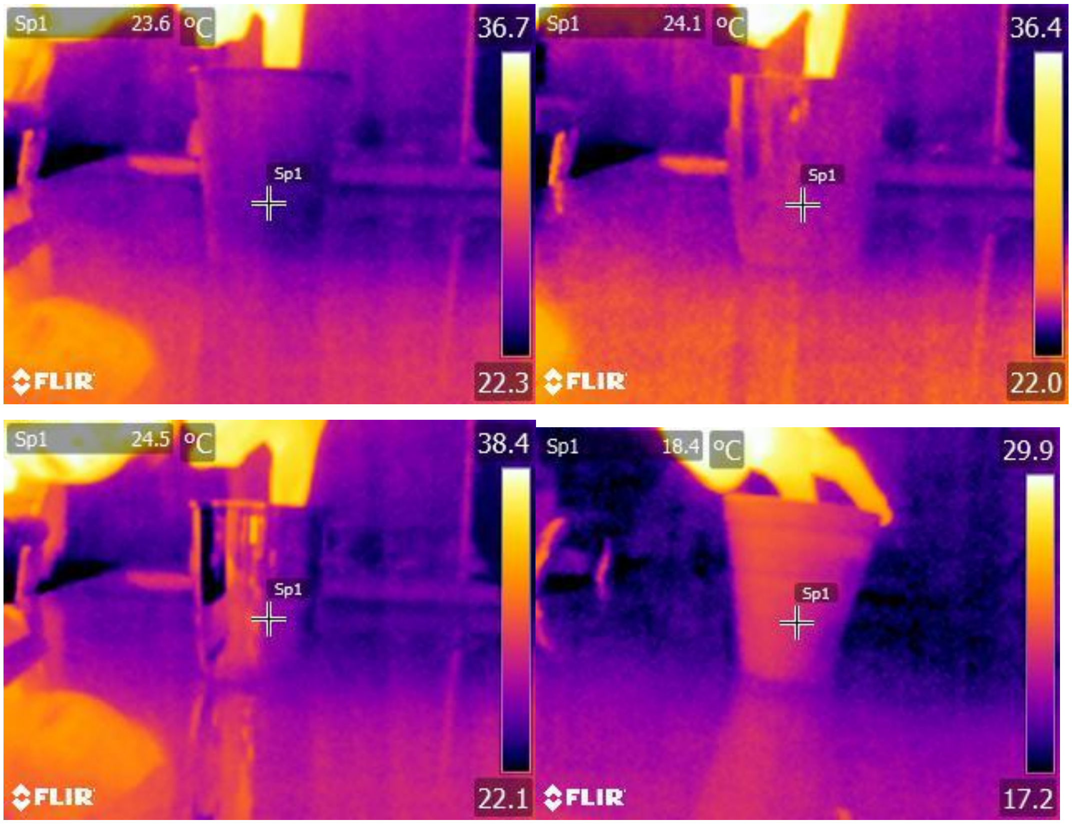


Figure 7.8 Infrared images of finger in four cups.

7.6 Example - Metal in Cups

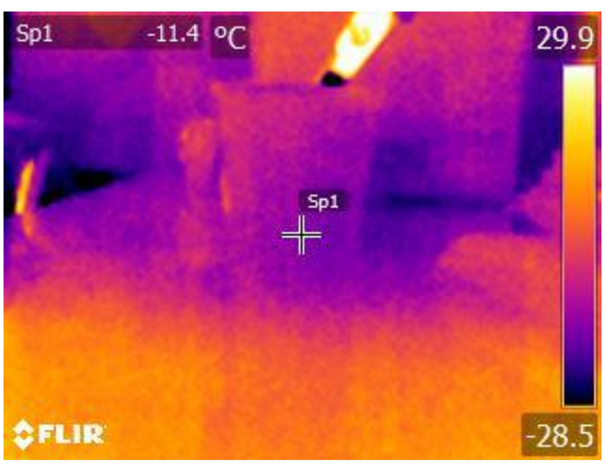


Figure 7.9 Infrared images of scissor in cup.

7.7 Example - Various Color Liquids in Bottles

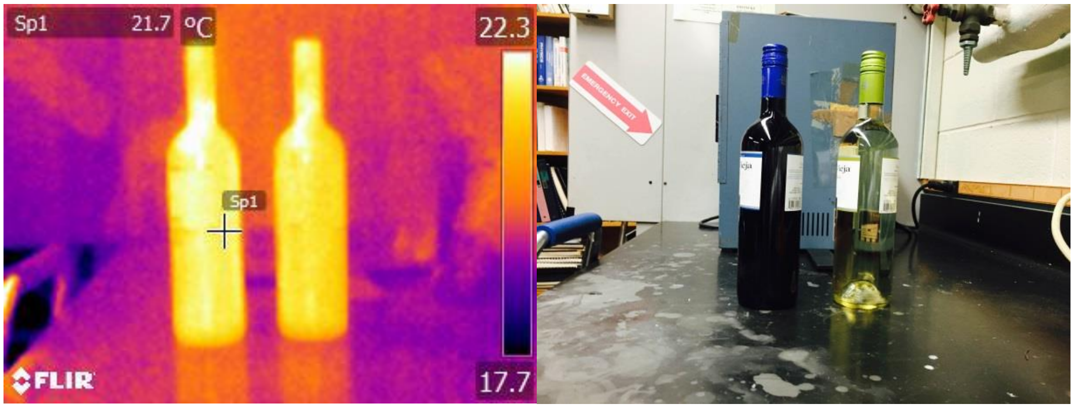


Figure 7.10 Infrared images of bottles of red wine and white wine.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

Compared with imaging in visible light, infrared (IR) imaging has abilities to convey additional information.

We measured emissivity of cups of four different materials and found that the temperature has some effect on the emissivity of objects. From the infrared images of ice in the four cups, we found different materials had different properties. Some of them are easy to be detected by the IR camera, and the others are not. We cannot judge the color of liquid with IR camera. We cannot see fingers or scissors in the cups.

Our measurements of the emissivities of the cups of a variety of materials are in accord with the emissivities in the literature.

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