Measurement of the Thermal Response of Inkjet Printheads using Infrared Thermography

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Abstract

The subject of this investigation is the non-contacting measurement of the thermal response of an ink jet device in its micro environment. Discussion of the techniques, experimental setup, and recommendations required in making thermal measurements using infrared thermography are presented. Two applications in which this was used were the coupling of the measurements with a numerical thermal model to determine the die bond thermal conductivity and the comparison of the thermal measurements of the silicon heater plate, silicon channel plate and substrate of the Ink Jet Printhead. The results of these activities agree very well with the manufacturers measured thermal conductivity of the die bond material and the numerical thermal model both for jetting and dry firing of the print head.

Introduction

Thermal radiation is one of the main components in heat transfer that requires no conducting median to transfer energy unlike conduction and convection. Radiation can be viewed as the propagation of electromagnetic waves. Therefore, radiation can be described by its wavelength λ (µm) and frequency ν (Hz.). These properties are related by the following relationship when propagating in a medium and c is the speed of light.

$$\lambda = \frac{c}{\nu}$$

The thermal radiation spectrum is considered approximately from .1 to 100 µm which includes the visible, infrared and part of ultraviolet (UV) where it is pertinent to heat transfer. Figure 1 shows the order in which the spectrum is identified as a function of its wavelength. Ref. [1,2]

Since all objects emit thermal radiation, it is known through Planck's Law that the radiant energy increases with increasing temperature. Thus, the amount of emitted infrared radiation is a function of the object's temperature. The relationship that governs this is the Stefan - Boltzmann Law

$$E = \varepsilon\sigma T^4$$

where E is the emissive power, ε is the emissivity factor, σ is the Stefan-Boltzmann constant (5.67×10^{-12} W/cm^{2}K), and T is the absolute temperature of the object. The radiosity is termed as the total radiation that accounts for all the radiant energy emitting from the surface, reflecting, and transmitting through the object. Radiation emitted from the surface of the object will be bounded by a spectral distribution as well as a directional distribution. The total radiation is given by the following expression

$$\varepsilon + \tau + \rho = 1$$

where ρ is the reflection, τ is transmittance and ε is the emissivity. The sum of the radiation sources must be equal to 100%. As it is now seen, the material property of the object becomes very important in understanding how much radiated power is being emitted. In addition, as given by Kirchhoff's Law, the emitted energy must be equal to energy absorbed at equilibrium. Ref. [1,2]

A true blackbody will have emittance of 1 and no reflection nor transmittance. Emissivity is the ratio of the

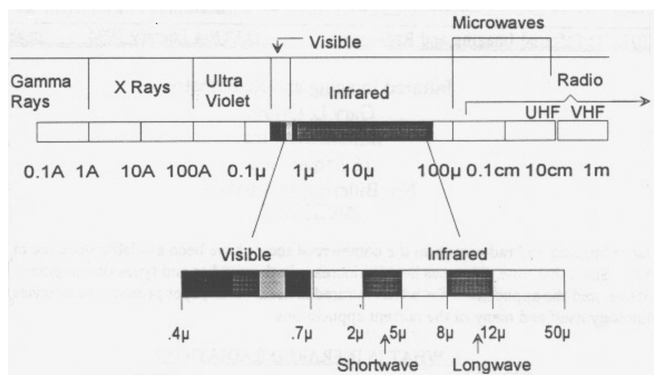

Fig. 1 Electromagnetic Spectrum Ref. [1]

energy emitted by the object with respect to a blackbody at the same temperature. Therefore, in order to calculate the temperature of an object using a thermal imaging radiometer, it is important to know what the emissivity is.

The Infrared Imaging Radiometer used in the following measurements is the Model 760 made by Inframetrics Inc.

This unit allows for three different selections of the system response curves in the infrared spectrum which is the short-wave (SW), long-wave (LW) and broadband (BB). Figure 1 identifies where the SW and LW resides and the BB is essentially composed of both SW and LW as a function of the Relative System Response curve. This curve is produced by Inframetrics as shown in Figure 2. The broadband was selected for all measurements made. Ref. [1]

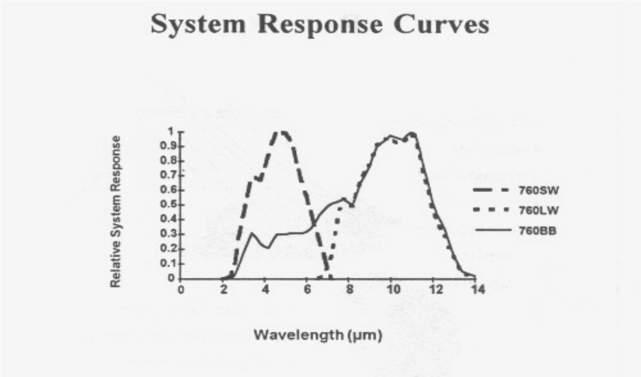

Figure 2. Ref. [1]

Infrared Measurements

The way an infrared radiometer works in being able to making a thermal measurement is by the infrared detector. The Inframetrics unit uses a photon detector in order to sense the infrared energy. This is a semiconductor that produces a signal proportional to the amount of photon flux that it receives and requires cryogenic cooling for it to work. The infrared energy passes through the lens of the radiometer to a reflective galvanometer scan mechanism that creates the image of the object emitting the infrared radiation. The image is produced by the oscillating movement of the horizontal and vertical mirrors to move the field of view of the detector in two dimensions. During this process it is viewing a thermal reference at regular intervals in order to measure the temperature of the object. As the radiation passes through the scanner, it is sent to the IR detector and the information is processed through the electronics. From here the image is presented to television monitor for post processing and viewing the thermal measurements. Ref. [1] There are several good reasons for using infrared thermography in making temperature measurements. It is non-contacting so one does not have to be concern about the thermocouple having an effect in the measurement itself. It has a tremendous advantage in measuring the temperature of a particular area where a thermocouple may be too large. The other advantage with this type of system is that it offers a microscope lens and 3X telescope but also can electronically zoom in on miniature locations. The resolution element size is 30 μm for the combined 3X telescope and the microscope lens and the field of view is 5.1 mm in the horizontal and 4.0 mm in the vertical. Ref. [1] In this application, it is well suited to measure the temperature of the silicon chips that makes up the printing transducer of a Xerox Thermal Inkjet Printhead.

Experimental Techniques for Determination of the Emissive Material Property

However, before the temperature measurements can be made the emissivity of the object must be known. Also the radiometer and the object should be perpendicular to one another. There is one main disadvantage when using this type of infrared radiometer on an object that has a low emissivity such as silicon and a high reflectance. It is called the narcissus effect because it appears as a very cold black spot on the silicon. The cryogenically cooled IR detector is reflected off the very reflective surface of the silicon and back through the optics in which it sees itself. It will obviously cause a false temperature reading.

There is a couple of ways to avoid this problem. One very simple technique is to raise the emissivity of the surface to a known high value. This can be accomplished by spraying the surface of the object or adhering a material on the object where the value of the emissivity has been well established. An example of each type of these materials is black vinyl electrical tape where its emissivity is approximately 0.95 and Desenex foot powder as sprayed is approximately 0.93. This type of powder has found to be safe in spraying on electronic equipment without damage. Upon using either of these materials, the cold spot does not appear and the thermal measurements can be corrected by inputting its emissivity into the IR camera. To check for either of these materials emissivities, a simple experiment can be conducted by using a hot plate where the temperature is known and applying it to surface of the plate. Simply change the emissivity in the IR camera until the temperature equals that of the hot plate. This value is the emissivity for the applied material. Another inherent advantage of a high emissivity surface is that it will have a more accurate measurement of the temperature. Small errors calculated for the low emissivity material can give rise to higher temperature errors because of the background radiation reflected off of the object is playing a greater role than the emitted energy from the object. The background temperature in this case must be known more accurately. Frank Bryson of Infrared Technologies Inc. worked as a consultant to ensure proper techniques and understanding of experimental errors that could be involved in making thermal measurements using an Infrared Radiometer. Ref. [3]

The above technique essentially assumes that the temperature of the applied surface treatment is that of the actual surface itself. If the surface of the object is believed to have a known high emissivity and the measurement is desired to be made on the actual surface then there are several techniques that can be chosen in order to determine the emissivity of the object's surface. Some of these techniques are the Reference Emittance Technique and Reflectance Technique for opaque objects and the Transmittance Technique for non-opaque objects. Ref. [1]. The Transmittance Technique will not be discussed.

The Reference Emittance Technique involves the target in which the emissivity is being determined, a piece of cardboard wrapped with crumbled aluminum foil, and a reference material of known emissivity. This could be a high emissivity black paint, black electrical vinyl tape or foot powder. The crumbled aluminum foil wrapped over one side of the cardboard will serve as means to measure the background radiation. Set the emissivity of the IR camera to 1 and any external optics to one or their appropriate value. Input the background temperature and ensure no other radiating sources including yourself are reflecting off the target and background. Set the temperature units to what is called level units for measuring the thermal radiation. Place the reference material on the heated or cooled surface of the target and measure the reference source level as well as the target level. The known reference emissivity is denoted as E*ref*.. Measure the background level and use the following equation to compute the emissivity of the target. Ref. [1]

$$Emissivity = \frac{(\text{Target Level} - \text{Background Level})}{(\text{Reference Level} - \text{Background Level})} \text{E}ref\,.$$

(Reference Emittance Technique for experimentally determining the emissivity)

The Reflectance Technique requires a hot and a cold source to be reflected off the target. Following the similar instructions as given in the reference emittance technique are as follows: set the emissivity to one in the camera, external optics to one or the appropriate value, and input background temperature in the IR camera. Choosing the cold source first, point the IR camera at the target and focus on the reflection of this source. After measuring its level for the cold source, repeat the process using the hot source. Measure the level of the hot and cold sources each. The emissivity is computed as follows:

$$Emissivity = 1 - \frac{(\text{Hot Level Reflected} - \text{Cold Level Reflected})}{(\text{Hot Level} - \text{Cold Level})}$$

(Reflectance Emittance Technique for experimentally determining the emissivity)

Applications of Infrared Thermography

The first application using infrared thermography was to determine the thermal conductivity of the diebond material used in the thermal inkjet printhead. The objective of this experiment is to use this information in the thermal performance simulations of the printhead. Thermal conductivity measurements can be very challenging to determine even though the manufacturer's may claim to be within a 5% accuracy. Although this can be true, operator to operator variation can be another variable contributing to the amount of error as well as the degree of uncertainty in the preparation of the samples to be tested.

A bench was made specifically for the radiometer to placed on and have the capability to be position precisely with respect to the target. At the other end of this table, the printhead is located by a mounting fixture to be viewed by the camera. To avoid any other thermal radiation sources a cardboard box was used to shroud the printhead leaving only the front plane open. The other advantage in the design of the bench is that the operating equipment is located under the bench where one's hands can not be accidentally shown as background radiation. The microscope objective and 3X telescope lens were used. The foot powder was sprayed on the front face of the printhead where the chip was attached to the substrate of the device. The sprayed coating is assumed to be thin enough that its thermal gradient is negligible as compared to its real surface temperature. The emissivity of the powder entered into the camera was 0.93. The printhead was dry fired in determining the thermal conductivity of the silver epoxy.

The thermal conductivity was determined as a function of the diebond process used in the manufacture of thermal inkjet printhead. To accomplish this, a transient thermal numerical model was used in comparing the experimental data. The assumption from 0 to 1 seconds is made that the conduction is dominating in this time frame with negligible radiation and convection effects. The thermal model was developed by Mehmet Sengun at the Xerox Corporation. In using his model, the thermal conductivity was varied and compared to the experimental data. The infrared camera was used to collect the data and an averaging line was drawn across the width of the silicon chip using Inframetric's Thermagram 95 post processing software. By matching the simulation results and the IR measurements, the thermal conductivity was found to be 1.7 W/mK which is the exact value supplied by the manufacturer. This is shown in Table 1. The temperature data is the relative difference with respect to the ambient temperature. In addition, a 0.005 in. diameter thermocouple (TC) was placed at the silicon chip's center half where the data was sampled at 0.01 second intervals. This data, also presented in Table 1, is in excellent agreement with the thermal simulations and the IR measurements.

Time (sec)	Simulation with K=1.7(W/mK)	TC(C)	IR(C)
0.2	1.98	1.72	N/A
0.4	2.32	2.31	N/A
0.6	2.54	2.49	N/A
0.8	2.57	2.88	N/A
1	2.96	3.07	2.96

Table 1. Numerical Thermal Simulation and Experimental Data using Infrared Thermography (IR) and Thermocouple (TC)

The next application was to use the information gained from the previous experiment and compare this to the thermal numerical model of the thermal inkjet printhead. The camera was supported using a tripod and the printhead was located independent of the camera's datum.

The printhead power input of the dry fire run was made first at 1 watt and then 9 watts. This was done to decouple the jetting mode to understand how the conduction and the convection part of the model correlated to the experimental data. The printhead was sprayed with the foot powder in order to have the entire front face at the same emissivity. Tables 2 to 5 show the comparison of the 1 and 9 watt power input to the printhead. Figure 3 is enclosed for visual reference of the front face of the print head as what the radiometer would actually be seeing except that is at a

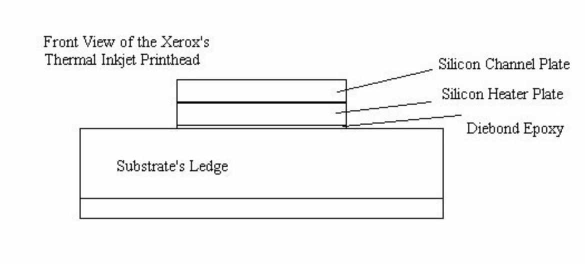

Figure 3. Front View of just the chip and substrate of Xerox's Thermal Inkjet Printhead

higher magnification. The microscope objective and 3X telescope lens were used. Two particular areas of interest were the silicon heater plate and the substrate's ledge where the silicon chip is located. The dry fire data ran for 16 minutes for each power level. The temperatures are in absolute. From Tables 2 through 5, there appears to be a very good correlation between the thermal model and the IR thermal imaging data.

Time(sec)	Experimental IR (C)	Model (C)	Difference
119	40	38.7	3.20%
241	45.5	45.5	0.00%
363	50.1	50.5	-0.80%
485	53.2	54.1	-1.70%
607	55.3	56.8	-2.70%
729	57.4	58.7	-2.30%
851	58.7	59.8	-1.90%
960	60	60.7	-1.20%

Table 2. Dry Firing of a Thermal Inkjet Printhead at 1 Watt sensed at the Substrate's ledge below the chip.

Time(sec)	Experimental IR (C)	Model (C)	Difference
119	41	40	2.40%
241	46.6	46.8	-0.40%
363	51.1	51.8	-1.40%
485	54.3	55.5	-2.20%
607	56.4	58.1	-3.00%
729	58.7	60	-2.20%
851	59.8	61	-2.00%
960	61.3	62	-1.10%

Table 3. Dry Firing of a Thermal Inkjet Printhead at 1 Watt sensed at the Silicon Heater Plate.

Time(sec)	Experimental IR (C)	Model (C)	Difference
1	38	38.2	-0.50%
5	49.3	45.7	7.30%
10	55.7	51	8.40%
16	60	56.1	6.50%
19.75	63	59.3	5.90%
25	65.6	63	4.00%

Table 4. Dry Firing of a Thermal Inkjet Printhead at 9 Watt sensed at the Substrate's Ledge below the Si chip.

Time(sec)	Experimental IR (C)	Model (C)	Difference
1	46.2	49.7	-7.60%
5	57.2	57.5	-0.50%
10	63.1	62.9	0.30%
16	67.9	68	-0.10%
19.75	70.2	70.6	-0.60%
25	73.7	74.6	-1.20%

Table 5. Dry Firing of a Thermal Inkjet Printhead at 9 Watt sensed at the Silicon Heater Plate.

The collecting of data during actual wet firing of the printhead was a challenge. This involved two conditions in order to the collect data using the Infrared radiometer. First, a shield was constructed using a polyester type film to protect the lens of the camera from the fired ink droplets. This film is essentially a high transmitter of IR and has not been found to effect the temperature measurements. The film in this experiment is the material used in insulating windows and by using a hot air gun the material would stretch leaving behind no wrinkles. The next issue was concerning how to spray the powder on the printhead without clogging the jets. This was accomplished by using a molding silicone that was poured on to a small glass sheet and ensuring that it was spread across it in a thin manner. By using a razor blade to slice the silicone into a small rectangular piece, it was place onto the front face of the print head via a microscope allowing only the jets to be covered. Spray the high emissivity powder material on the print head and lift the silicone slice off. The silicone slice left behind a perfect pattern of exposing only the jets with zero clogs.

The 1 watt power input was fired for 9 minutes and the second case was 9 watt for 80 seconds. The data presented here is only of the substrates ledge as shown in Table 6 and Table 7 for each of the power levels. The silicon heater

Time(sec)	Experimental IR (C)	Model (C)	Difference
15	32.3	31.2	3.40%
30	33.4	32.2	3.60%
60	35.3	34.1	3.40%
180	41.7	40.8	2.20%
300	45.5	45.4	0.20%
420	47.7	48.8	-2.30%
540	49.4	51.1	-3.40%

Table 6. Wet Firing of a Thermal Inkjet Printhead at 1 Watt at the Substrate's Ledge below the Si chip.

plate measurements is not presented because the ink was accumulating in some of the areas around the face of the print head creating an inaccurate temperature reading. Thus the substrate ledge temperature was measured and again found to correlate very well with the numerical model.

Time(sec)	Experimental IR (C)	Model (C)	Difference
10	48.5	46.7	3.70%
20	54.3	52.5	3.30%
30	58.5	57.6	1.50%
40	61.6	62.4	-1.30%
50	64.8	66.8	-3.10%
60	68.1	70.8	-4.00%
80	72.9	78.3	-7.40%

Table 7. Wet Firing of a Thermal Inkjet Printhead at 9 Watt at the Substrate's Ledge below the Si chip.

Conclusion

This tool proved to be valuable in helping to understand what the thermal conductivity of the diebond adhesive was and comparing the numerical simulations with experimental measurements. The thermal imaging post-processing software package for the infrared camera is a great tool for analyzing the thermal data. Again, understanding your setup and background is very important before taking any measurements. Decoupling the jetting response of the printhead had helped confirm our understanding of the model and also at the silicon plate. It was especially challenging in avoiding the lens of the radiometer from getting wet by the jetting printhead while trying to make a non-contacting thermal measurement. Upon comparing the experimental data with the numerical simulation data for both the jetting and non-jetting response of the printhead, it not only suggests validation of the model but also the specified material properties such as the diebond adhesive.

References

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