Estimating Temperature Rise Due To Flashlamp Heating Using Irreversible Temperature Indicators

Abstract

One of the nondestructive thermography inspection techniques uses photographic flashlamps. The flashlamps provide a short duration (about 0.005 sec) heat pulse. The short burst of energy results in a momentary rise in the surface temperature of the part. The temperature rise may be detrimental to the top layer of the part being exposed. Therefore, it is necessary to ensure the nondestructive nature of the technique. Amount of the temperature rise determines whether the flashlamp heating would be detrimental to the part. A direct method for the temperature measurement is to use of an infrared pyrometer that has much shorter response time than the flash duration. In this paper, an alternative technique is given using the irreversible temperature indicators. This is an indirect technique and it measures the temperature rise on the irreversible temperature indicators and computes the incident heat flux. Once the heat flux is known, the temperature rise on the part can be computed. A wedge shaped irreversible temperature indicator for measuring the heat flux is proposed. A procedure is given to use the wedge indicator.

Keywords: Temperature, flashlamps, thermography, nondestructive evaluation

Introduction

Heat is imparted to the part under inspection in the active thermography nondestructive inspection techniques. The heat is applied in many different ways. One of the methods uses a short heat pulse from the flashlamps. This paper provides an indirect technique to estimate the temperature rise due to the flash. Carslaw and Jaeger provide solutions to a variety of the heat conduction problems including that of a pulse heating. Parker et al. used the flashlamps to determine thermal properties such as diffisivity, heat capacity and conductivity. They measure the maximum front and back surface temperatures and use these measurements to calculate the thermal properties. Parker et al. derive their equations from Carslaw and Jaeger. Spicer gives equations for the surface temperature due to various external heat sources.

The flash duration is about 0.005 sec. Because of the short flash duration, relatively little amount of heat is imparted. The part temperature on the surface rises until end of the flash duration and then drops quickly due to the heat radiation and convection from the surface and the heat conduction into the part. The temperature rise on the part surface can be high enough to damage the top layer of the part. When the part is touched after the flash, it does not feel as hot. This is because of the rapid decay in the temperature after the flash and also because the hand acting as a heat sink in absorbing the heat and thereby reducing the temperature actually felt by the hand. This is also the problem with any contact type sensor. The temperature rise measured by the sensor will depend upon the mass (or the thermal contact resistance) of the sensor material, the heat travels through before reaching the active element. Thus, it is impossible to measure the temperature rise due to flash using a contact type probe, which is suitable for a steady state (or a slowly changing) temperature measurement. A radiation type sensor is suitable only if the response time is much shorter than the pulse duration. This paper provides an inexpensive technique that uses the irreversible temperature indicators to estimate the temperature rise.

The irreversible temperature indicator (labels) are used to indicate the maximum temperature reached on the part at the location of the label. In this paper, a brand of labels called Tempilabel Temperature Monitor was used. The indicator comes in the form of a label that has an adhesive backing. It has many ¼" diameter dots arranged in a row. Each dot is rated at a unique temperature. Each dot would change the color from white to black upon exposed to a temperature at or above the its rated temperature printed next to it. In a given label, the rated temperatures of the dots are equally spaced to provide an operating temperature range. The construction of the label is illustrated in Figure 1. The top layer has transparent windows that coincide with the dots. The bottom layer has adhesive on both sides. The dots are made from a black color paper. The front surface of the dots is coated with a thin layer of white-color temperature-sensitive compound. When the flash heat is incident on the label, the incident surface of the label heats up shortly. Depending upon the maximum temperature reached at the temperature sensitive compound, some dots will change their color to black. When a dot changes the color, the temperature sensitive compound burns away exposing the black color substrate. The label can be attached to the hardware. When the lamps are flashed over the label, the label will indicate the maximum temperature reached by the label and not by the hardware behind it. Thus, the label can not be used directly to measure the temperature rise. Instead, it is used to estimate the heat flux incident on the label. The flux is then used to calculate the temperature rise on the desired hardware receiving the same heat flux.

Theory

The temperature dots are stuck to the adhesive of the bottom layer. The dot can be separated from the bottom layer by peeling. The isolated dots can be exposed to the flash heat in two ways. In the first technique, called the dot front-side temperature measurement technique, the dot front (white) side faces the flash. In the second technique, called the dot unexposed-side temperature measurement technique, the black underside of the dot faces the flash and the temperature rise is measured on the (white) unexposed side. In the both techniques, the goal is to estimate the absorbed heat flux from the indicated temperature on the dots.

Let us first consider a situation where the temperature is estimated or measured on the front surface of the dot or the part. Since the temperature compound is on the front surface, temperature indicated by the dots is for the front surface only. The flash duration is typically 0.005 sec. Therefore; it is considered a short heat pulse. The change in the surface temperature is given by the following equation, which is derived from the short pulse equation given by Spicer,

(1) $$\Delta T^{f}(t)=\frac{2\varepsilon_f bH}{\beta\sqrt{\pi}}\left[\left(\sqrt{t+\Delta t}-\sqrt{t}\right)+\sum_{n=1}^{\infty}\left\{\frac{\Delta t e^{\left(\frac{-\tau_n}{t}\right)}}{\sqrt{t}}\right\}\left[1+\frac{2\tau_n}{t}\left(1-\frac{1}{\pi}\right)\right]\right]$$

where,

(2) $$\tau_n = \frac{n^2 d^2}{a}$$

(3) $$\alpha = \sqrt{\frac{k}{\rho c}}$$

(4) $$\beta = \sqrt{k \rho c}$$

(5) $$H = \frac{Q}{\Delta t}$$

ΔT^f = temperature change on the front surface (°C or °F),

t = time (sec or hr) measured from the end of the flash,

H = average heat flux incident on the surface, (cal-cm^{-2}sec^{-1} or BTU-ft^{-2}hr^{-1}),

Δt = flash time (sec or hr),

b = a dimensionless constant,

k = thermal conductivity, (cal- cm^{-1} -°C^{-1} s^{-1} or BTU- ft^{-1} -°F^{-1} hr^{-1}),

ρ = density (g- cm^{-3} or lbm- ft^{-3}),

c = specific heat (cal- gm^{-1} -°C^{-1} or BTU- lbm^{-1} -°F^{-1}),

a = thermal diffusivity, (cm^2 -sec^{-1} or ft^2-hr^{-1}),

β = thermal effusivity, (cal-cm^{-2} -°C^{-1}-sec$^{-1/2}$ or BTU-ft^{-2} -°F^{-1}-hr$^{-1/2}$),

ε_f = emissivity of the flashed surface (the dot front surface in this case),

d = layer thickness (cm or ft)

Q = total heat incident on the part per unit surface area (cal-cm^{-2} or BTU-ft^{-2}).

The above equation is identical to the equation provided by Spicer, except for the factor b. Equation (1) provides the maximum temperature at t = 0 for a thermally thick part. For a thermally thin part, the predicted temperature converges to a steady state value after a time approximately equal to about two flash durations. The right hand side of the above equation has two terms in the outer square bracket. The first term in the parenthesis is called the thick part response and the second term containing the summation sign is called the thin part response.

The temperature rise is defined as the maximum change in the temperature of the part. The above equation is valid for all part thickness. The equation can be broken down into two simple equations depending upon the part thickness. Let us define the threshold thickness d_c such that if $d \le d_c$ then the part is thermally thin. Otherwise, it is thermally thick.

A thermally thick part is such that the change in the surface temperature for a thermally thick part is given by the thick part response term in equation (1).

(6) $$\Delta T^f = \frac{2b\varepsilon_f H}{\beta\sqrt{\pi}}\left[\sqrt{t+\Delta t} - \sqrt{t}\right] \qquad \text{for } d \ge d_c$$

The temperature rise on the thick part is given by evaluating equation (6) at $t = 0$,

(7a) $$\Delta T^f_{max} = \frac{2b\varepsilon_f H\sqrt{\Delta t}}{\beta\sqrt{\pi}} \qquad \text{for } d \ge d_c$$

Parker et al. give the following equation for the temperature rise on the thermally thick part.

(7b) $$\Delta T^f_{max} = \frac{8b_1\varepsilon_f H\sqrt{\Delta t}}{3\sqrt{2\pi}\beta} \qquad \text{for } d \ge d_c$$

They introduce a correction factor b_1 to correct for the difference between the assumed shape of the heat pulse verses its actual shape. The two formulas are very close to each other if the correction factors are neglected.

A thermally thin part is such that the change in the surface temperature for a thermally thin part is given by the thin part response term in equation (1). The first term of equation (1) is neglected and the second (summation) term of the equation simplifies the equation to,

(8a) $$\Delta T^f(t) = \frac{2b\varepsilon_f H}{\beta\sqrt{\pi}}\left[\frac{1.477\Delta t\sqrt{\alpha}}{d}\right] \qquad \text{for } d \le d_c$$

This equation simplifies to,

(8b) $$AT^*(t) = \frac{1.6666b\varepsilon_f H\Delta t}{dc\rho} \qquad \text{for } d \le d_c$$

There is no time dependent term in the above equation. Equation (8) assumes that the part is so thin that it heats up uniformly throughout its thickness. Assuming no losses, this temperature rise shall be given by equating the absorbed heat to increase in the heat content of the part as,

(9a) $$\varepsilon_f H\Delta t = dc\rho\Delta T^f_{max} \qquad \text{for } d \le d_c$$

From the above equation the temperature rise is given by,

(9b)

$$\Delta T^f_{max} = \frac{\varepsilon_f H \Delta t}{d c \rho} \qquad \text{for } d \le d_c$$

Since, the above equation is independent of time; it shall also provide the steady state temperature rise. Thus,

(10)

$$\Delta T_{steady} = \frac{\varepsilon_f H \Delta t}{d c \rho} \qquad \text{for all } d$$

Equations (8) and (9) must provide same estimate for the temperature rise. Therefore, equating equations (8) and (9), we get the value of the constant b to be 0.6. The constant b_1 then can be evaluated to be 0.636. The threshold thickness can be determined by equating equations (7) and (9).

(11)

$$d_c = \frac{\beta\sqrt{\pi \Delta t}}{2bc\rho}$$

It can be shown that,

(12)

$$\Delta T^f_{max} = \frac{d}{d_c} \Delta T_{steady} \qquad \text{for } d \ge d_c$$

and

(13)

$$\Delta T^f_{max} = A\ T_{steady} \qquad \text{for } d \le d_c$$

If we measure the temperature rise on the dots then the heat flux incident on the dots is given by,

(14)

$$H = \frac{\Delta T^f_{max} \beta}{2b\varepsilon_f} \sqrt{\frac{\pi}{\Delta t}} \qquad \text{for } d \ge d_c$$

and

(15)

$$H = \frac{\Delta T^f_{max} d c \rho}{\varepsilon_f \Delta t} \qquad \text{for } d \le d_c$$

In order to chart the temperature response, the temperature on the front surface is normalized by the steady state temperature rise $\left(\frac{\Delta T^f}{\Delta T_{steady}}\right)$. This quantity is called the temperature ratio. Similarly, the thickness is normalized by the threshold thickness $\left(\frac{d}{d_c}\right)$. This quantity is called the thickness ratio. Figures 2, 3, 4 and 5 plot the temperature ratio response for thickness ratios of 1.0, 0.5, 0.1 and 5.0. These charts provide comparison of the temperature response by equations (1), (12) and (13). Equation (1) is termed 'Thick & Thin', equation (12) is termed 'Thick' and equation (13) is termed 'Thin' in these charts. The computation uses thermal properties of the temperature indicator label. The absorbed heat flux is 18.15 cal-cm^{-2}sec^{-1} in the charts.

When using the dot unexposed-side temperature measurement, the temperature change on the unexposed-side of the label is given by Parker et al. as follows for the long times,

(16)
$$\Delta T^b(t) = \frac{\varepsilon_b H \Delta t}{\rho c d}\left[1 + 2\sum(-1)^n e^{\left(\frac{-n^2\pi^2}{d^2}\alpha t\right)}\right]$$

where, ε_b = emissivity of the dot backside (black color side) of the dot. The maximum temperature reached by the unexposed surface is given by the first term in the above equation. Thus,

(17)
$$\Delta T^b_{max} = \frac{\varepsilon_b H \Delta t}{dc\rho}$$

If the temperature is measured on the unexposed side of the dot, then the incident heat flux is given by,

(18)
$$H = \frac{\Delta T^b_{max} dc\rho}{\varepsilon_b \Delta t}$$

Estimate Heat Flux

Dot Front-side Temperature Measurement

Select a Tempilabel with a suitable temperature range. Peel off the top transparent layer that covers the temperature indicating dots. If the dot thickness is more than the threshold thickness, then there is no need to peel the dot off its backing. Otherwise, peel the dots off the backing and stick them on an edge of a double back adhesive tape with less than a third area of each dot sticking to the tape. Measure the dot thickness'. Locate the dots at the center of the hood opening. Set the equipment to the correct setup for the technique. The label temperature will be the ambient temperature at this time. Flash the lamps. Read the highest temperature indicated by the dots. If all dots have been blackened, then use a label with a higher temperature limit and expose the dots to the flash. If none of the dots have been blackened, then use a label with a lower temperature limit and expose the dots to the flash. Ideally, the selected label should provide blackening of half of its dots when exposed to the flash. This may take a bit of trial and error. Subtract the ambient temperature from the highest indicated temperature to obtain the temperature rise. Compute the threshold thickness using equation 11. If the dot is thermally thick, use equation (14); otherwise use equation (15) and compute the incident heat flux.

Dot Unexposed-side Temperature Measurement

Expose the backside of the dots to the flash. Measure the temperature rise. Compute the incident heat flux using equation (18).

- **Temperature Rise Estimation**

Once the incident heat flux is known, determine the threshold thickness for the part that needs to be exposed to the flash with the same intensity. Compute the temperature rise using either equation (7) or (8) whichever applicable. Alternately, equations (9), (12) or (13) may be used to do the same.

Experiments

A flash equipment that is part of a thermography system by Thermal Wave Imaging, Inc. was used. It uses a 25.4 cm wide x 30.5 cm high x 42 cm deep illumination shroud (hood) assembly. It contains two 20.3 cm long Xenon flashtubes in parabolic reflectors with Pyrex shields located inside the hood. See Figure 6. Out of the six sides of the hood, one is open. The open side is usually in contact with the part during the flash to limit leakage of the intense flash. The lamps are powered by two Balcar S. A. model 6400 ASYM sources. The setting was chosen to provide the maximum available power, which is 12800 J. The electrical discharge time that is provided in the Balcar manual is 0.00047 sec. The thermal pulse time is thought to be about 0.005 sec. The filaments in the lamps heat up during the discharging of the power sources. The lamp tubes around the filaments also heat up. The cooling of the filament and the tube are slow processes compared to the process of electrical discharging of the source. Thus, the heat pulse is longer than the electrical pulse. The Pyrex shield over the lamps allows the visible light to pass through but reduces the transmission of the thermal radiation. The shield heats up due to the flash and acts as a secondary source of thermal radiation,' -which is' very weak. An infrared camera used in the system has maximum frame rate of 60 Hz, which is not suitable to capture the temperature rise on the part. Tempilabel No. 8D-210/99 was used. It had 8 dots. The lowest rated temperature was 99 °C. The highest rated temperature was 177 °C. The rated temperatures were spaced at about 11 °C.

The ambient temperature was 15.6°C (60°F). The following table provides the temperature rise measured on the dots in the both techniques and the respective dot thickness'. The values of the thermal properties of the dots and the flash duration are also tabulated. Using this data, the threshold thickness for the dots is computed. The threshold thickness is then used to compute the incident heat flux for both techniques. The results are tabulated below.

Table 1: The heat flux measurement on the dots

Quantity	unit	Value
d, Dot Front-side	cm	0.0127
ΔT^{f}_{max}, Dot Front-side	°C	138
d, Dot Unexposed-side	cm	0.0064

ΔT^{b}_{max}, Dot Unexposed-side	^{o}C	105	
k	cal- cm^{-1} -$^{o}C^{-1}$ s^{-1}	*429.84* x 10^{-6}	
c	cal-g^{-1}-$^{o}C^{-1}$	*0.32*	
r	gm-cm-'	*0 . 9 3*	
•	cal-cm^{-2}-$^{o}C^{-1}$-$sec^{-1/2}$	0.01131	
J		*0.85*	
		0.95	
t	sec	*0.005*	
d_c	cm	*0.004*	Equation (11)
H, Dot Front-side	cal-$cm^{-2}$$sec^{-1}$	*38.4*	Equation (14)
H, Dot Unexposed-side	cal-$cm^{-2}$$sec^{-1}$	41.8	Equation (18)

After knowing the incident heat flux, we estimate the temperature rise on the desired materials. We choose higher of the two estimates of the flux for the temperature estimation. Let us take two examples, one for a nonmetal and the other for a thin metal. The properties and the temperature rise are given below.

Table 2: The temperature rise estimation on the parts

Quantity	Unit	Value	
	Nonmetal		
d	cm	0.030	
k	cal- cm^{-1} -$^{o}C^{-1}$ s^{-1}	500 x 10^{-6}	
c	cal-g^{-1}-$^{o}C^{-1}$	0.375	
r	gm-cm^{-3}	1.18	
	cal-cm^{-2} -$^{o}C^{-1}$-$sec^{-1/2}$	0.0149	
		0.9	
d_c	cm	0.0035	Equation (11)
T	^{o}C	121.0	Equation (7)
	Metal		
d	cm	0.002	
k	cal- cm^{-1} -$^{o}C^{-1}$ s^{-1}	0.561	
c	cal-g^{-1}-$^{o}C^{-1}$	0.215	
r	gm-cm^{-3}	*2.699*	
	cal-cm^{-2} -$^{o}C^{-1}$-$sec^{-1/2}$	*0.570*	
		.09	
d_c	cm	0.1	Equation (11)
T	^{o}C	16.2	Equation (9)

Efficiency of the Flashlamp Heating

As a curiosity, we compute the efficiency of the flashlamps. We define the flashlamp heating efficiency as a percentage ratio of the heat incident through the hood window to the total electrical power consumed by the lamp during the flash. We will assume that the heat flux is uniform over the window. Thus, the efficiency is given by

(19) $$n = \frac{100HA_w\Delta t}{W}$$

where A_w = the area of the hood opening (window) in cm^2.

The hood window is 25.4 cm X 30.48 cm. A_w = 774.2 cm^2, W = 12800 J, t = 0.005 sec, H = 41.8 J-$cm^{-2}sec^{-1}$. Note, 1 J = 0.2388 cal.

Substituting we get an efficiency of 5.3%. Thus, this is a very inefficient way of applying the flash heat. This seems too low and make one wonder where the remaining 94.7% of the energy is dissipated. When the lamps are flashed the Pyrex shield and the lamp wall absorb most of the heat flux and provide a slow cooling. Moreover the emission from Pyrex is based on the surface temperature which not high enough to provide significant secondary radiation flux. The Pyrex shield and the tube thickness serve as a filter for the thermal radiation and let the visible radiation through. The temperature of the Pyrex shield surface is significantly higher on the lamp side but low on the part side. In all, secondary emission from Pyrex glass is very small. The Pyrex shield transmits the light wavelengths with high efficiency. Typically, 94% (emissivity = 0.94) of the incident thermal radiation on the Pyrex is absorbed. The remaining 6% is transmitted and reflected.

Discussion

Accuracy of this method is dependent on the accuracy of the values of the parameters used in the above calculations in addition to the accuracy of the Tempilabel temperature measurement. In the dot front-side technique, the temperature starts decaying as soon it reaches its peak. The decay is due to the conduction, radiation and the convection losses. This may or may not provide enough time to burn off the entire temperature sensitive compound that is rated at the maximum temperature reached by the surface. This will result in an underestimation of the temperature rise. In the dot unexposed-side technique, the maximum temperature is the steady state temperature and the decay in the temperature is not due to the conduction but due to the radiation and convection. Thus, the decay in the temperature is relatively slow and the measurement is more reliable.

The front-side technique does not use the dot thickness measurement, if the thickness is more than the threshold thickness. In the unexposed-side technique, the measurement of dot thickness is necessary. The heat flux estimated is proportional to the dot thickness. Thus, it is important to measure the thickness very accurately.

In, the front-side technique, the white color of the surface changes to black. If we assume that the significant component of radiation is in the visible range, then change of color from white to black implies change of the emissivity, which will introduce errors in the heat flux calculations. Therefore, the dot unexposed-side temperature measurement is more reliable.

The Wedge Indicator

In the unexposed-side technique, instead of exposing dots rated at different temperatures, a single irreversible indicator in the shape of a wedge or a step wedge (Figure 7) rated at a single temperature can be used. The maximum thickness of the wedge at which the temperature compound is burned off shall be noted. This is called the maximum burned thickness. Equation (18) is rewritten to provide an expression for computing the heat flux as below.

$$Q = \left(\frac{c\rho}{\varepsilon_b}\right)\left(T^b_{rated} - T_{ambient}\right)d \qquad (20)$$

The quantities in the first parenthesis are constant. The rated temperature for a given wedge indicator is also a constant. The only variables are the ambient temperature and the maximum burned thickness d. A plot of equation (20) with 100 °C rated temperature is given for five different ambient temperatures in Figure 8. The plot uses the values for the thermal properties of the dot indicators previously used. Once the burned thickness and the ambient temperature are known, the heat flux can be either read from Figure 8 or calculated from equation (20).

Conclusions

The paper provides an inexpensive method to measure the heat flux from the flash lamps. It also provides formulas to estimate temperature rise on the hardware receiving the flashlamp heat. This estimation can be used to determine whether the flash would have a detrimental effect on the exposed hardware.

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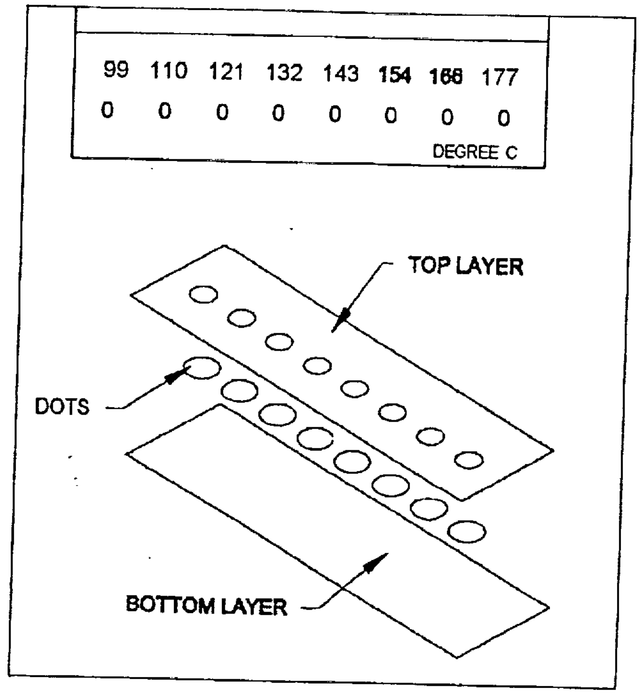

Figure 1 – The irreversible temperature indicator

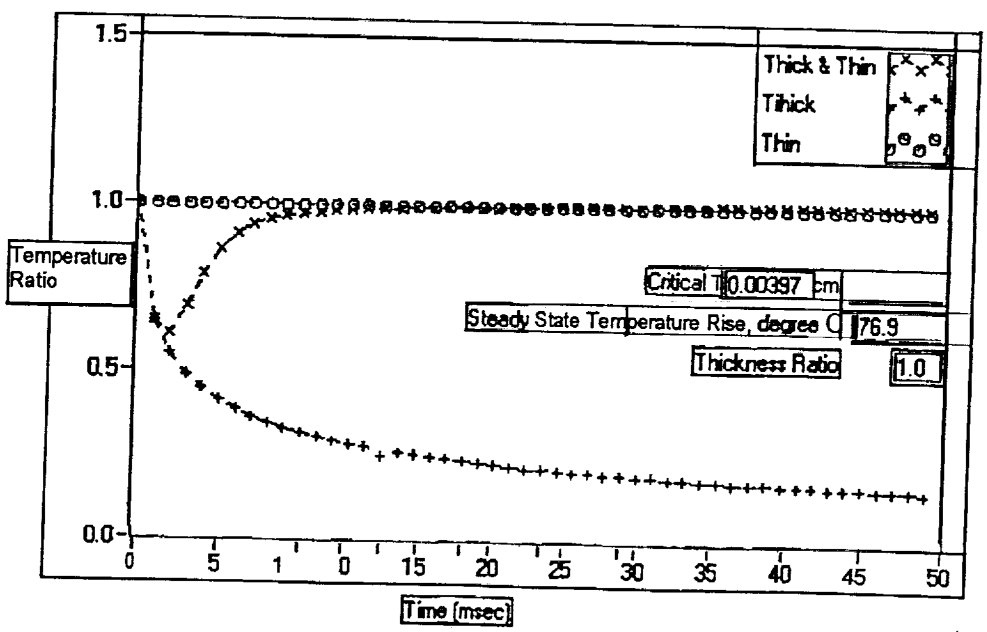

Figure 2 – Surface temperature response for thickness ratio of 1

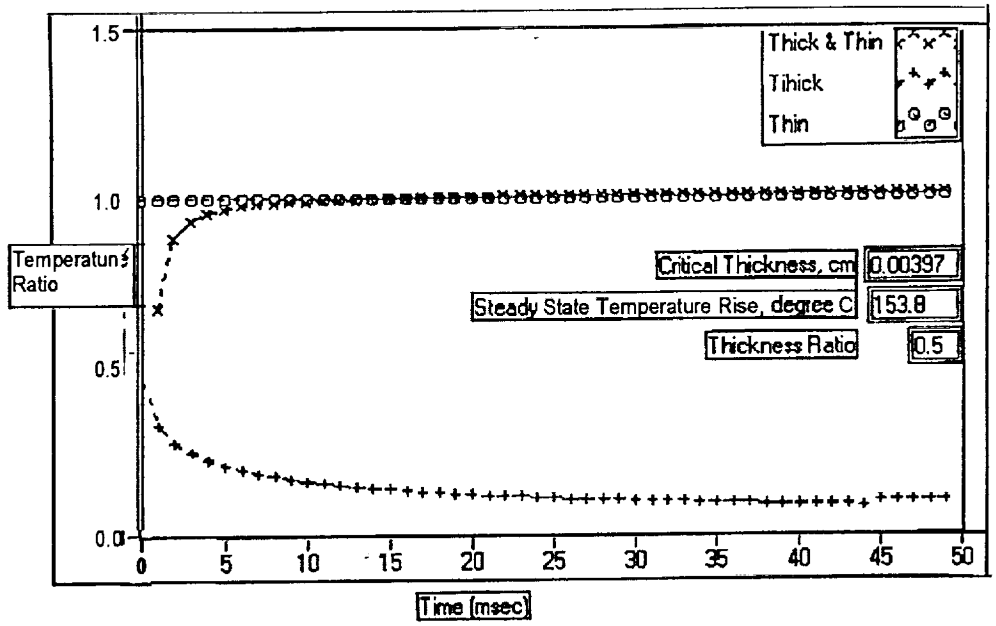

Figure 3 – Surface temperature response for thickness ratio of 0.5

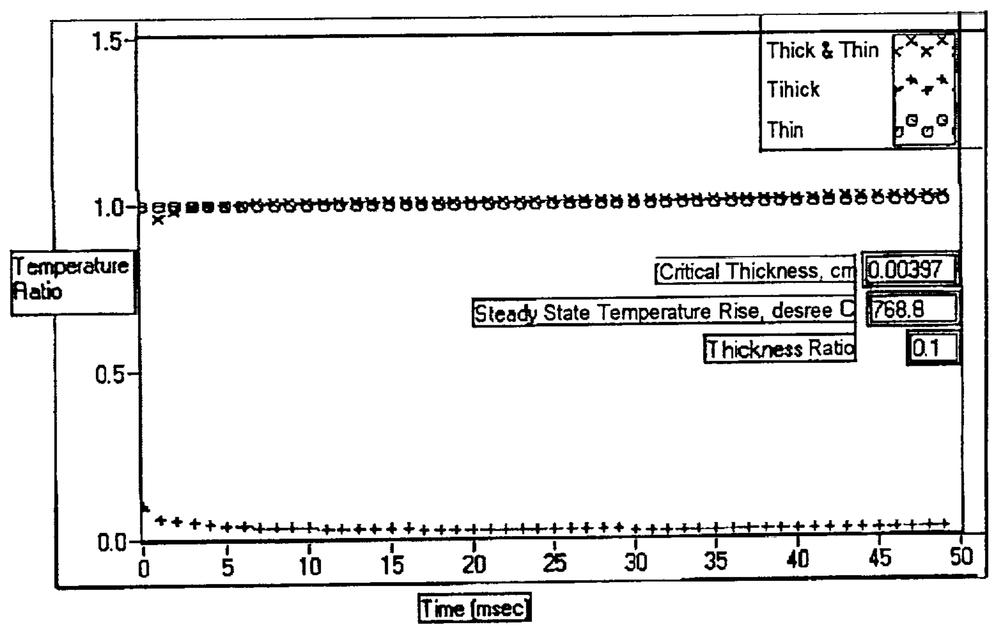

Figure 4 – Surface temperature response for thickness ratio of 0.1

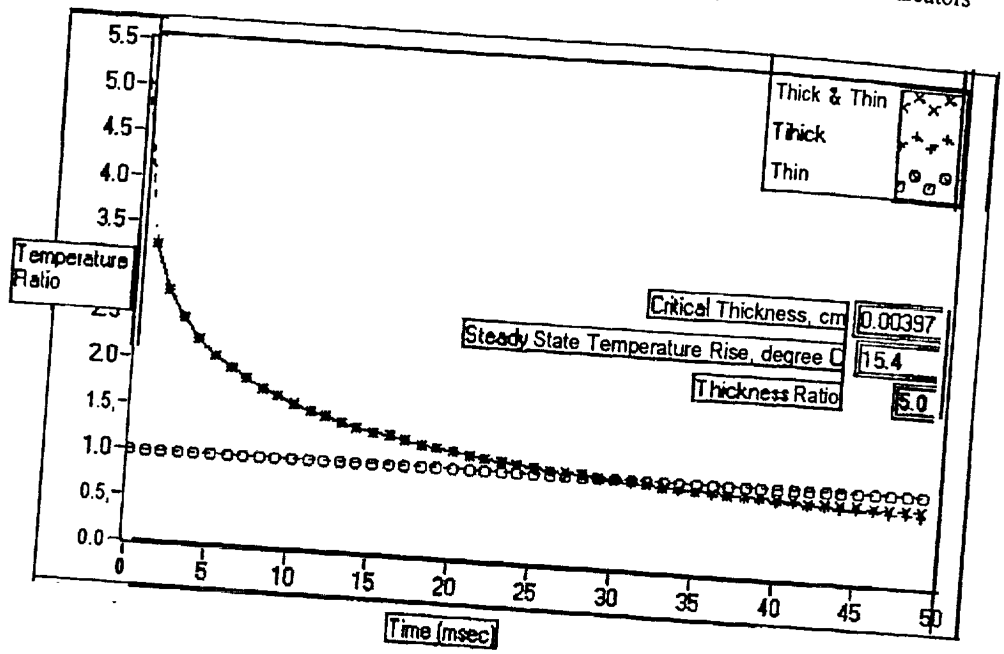

Figure 5 – Surface temperature response for thickness ratio of 5.0

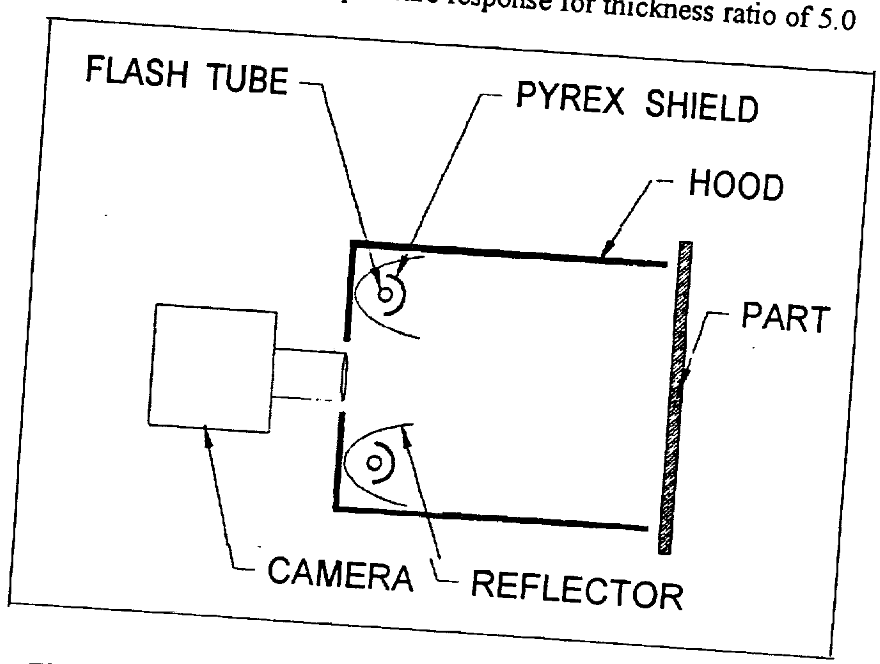

Figure 6 – Cross Sectional Schematic of the experimental set-up

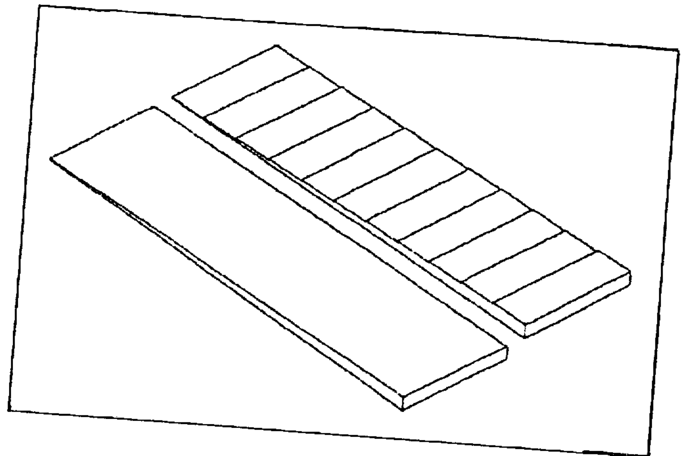

Figure 7 – Irreversable temperature indicator in the shape of a wedge or a step wedge

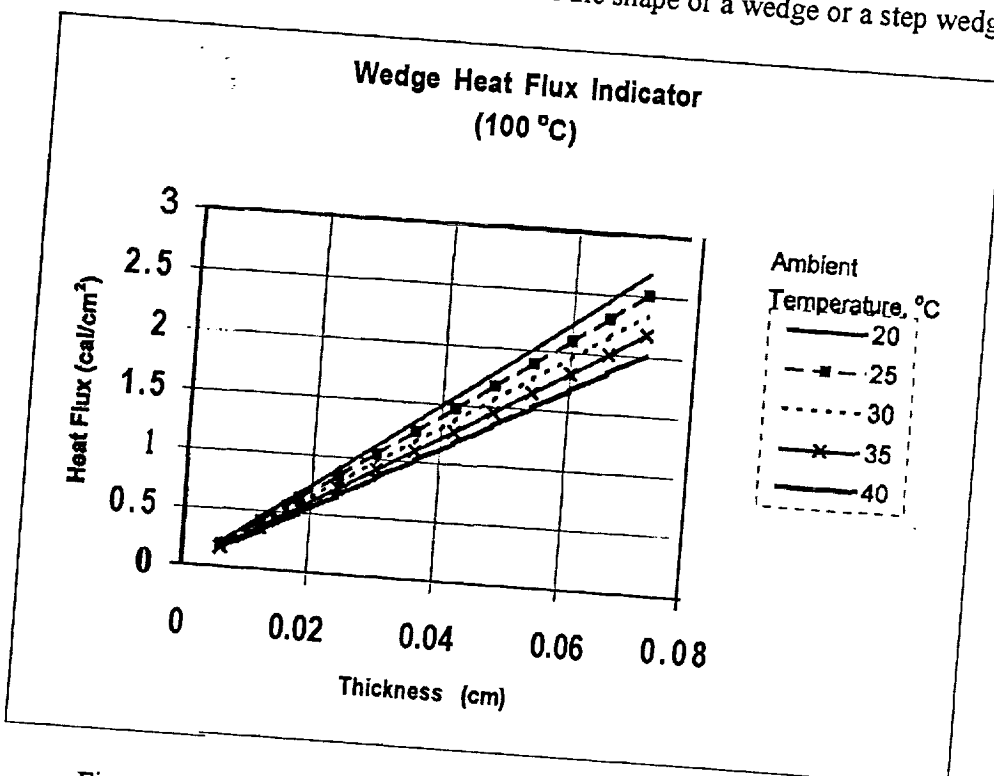

Figure 8 – The wedge indicator thickness versus the heat flux