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C-Therm TCi™ Principles of Operation

Introduction

The third generation of the technology expands the capabilities of this rapid, non-destructive testing instrumentation originally developed by Mathis Instruments to a whole new level. Designed to provide simple, highly accurate thermal characterization for lab, quality control and production environments, the C-Therm TCi Thermal Property Analyzer provides thermal analysis of solids, liquids, powders and pastes in less than 5 seconds. The TCi system measures thermal conductivity and effusivity of materials directly, based on the transient plane source method, and can provide user-inputted capabilities in the calculation of thermal diffusivity and heat capacity.

The system is comprised of a sensor, control electronics and computer software. The sensor has a central heater/sensor element in the shape of a spiral surrounded by a guard ring. The guard ring generates heat in addition to the spiral heater, thus, approximating a one-dimensional heat flow from the sensor into the material under test in contact with the sensor. The voltage drop on the spiral heater is measured before and during the transient. The voltage data is then translated into the effusivity value of the tested material. The conductivity is calculated from the voltage data by C-Therm's patented iterative method.

Effusivity is defined as the square root of the product of thermal conductivity, *k*, density, ρ and specific heat capacity, *Cp*, ($\sqrt{k \cdot \rho \cdot c_p}$) and has units of $\frac{W\sqrt{s}}{m^2 K}$. The TCi system measures effusivity directly, and determines conductivity as well from this measurement. The system automatically compensates for variations in sensor temperature, thus enabling reliable measurements at a wide range of temperatures (-50°C to +200°C).

For additional information please refer to Patent # 6,676,287**:** Direct thermal conductivity measurement technique, Patent ## 20040165645: Method and apparatus for monitoring substances and Patent # 5,795,064: Method for determining thermal properties of a sample.

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Theory

The heat equation in one dimension with a constant supply of heat per time per volume, *G'*, is given below:

$$\rho c_p \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial x^2} + G' \qquad (1)$$

If we assume one-dimensional heat flow and no thermal contact resistance at the interface between the sensor and sample under test, the temperature change on the sensor surface (x=0) is given by:

$$\Delta T(x = 0, t) = \frac{1.1284 G\sqrt{t}}{e_1 + e_2} \qquad (2)$$

Where: ΔT = change in sensor surface temperature (ºC)
G = power flux supplied to sensor (W/m^2)
t = time measured from start of process (sec)
e_1 = equivalent effusivity of sensor ($\frac{W\sqrt{s}}{m^2 K}$)
e_2 = effusivity of measured material ($\frac{W\sqrt{s}}{m^2 K}$)

The TCi system measures the voltage output of the sensor. If we can describe the change in sensor voltage vs. its temperature, we can then express the voltage change vs. time.

Sensor temperature calibration

To convert the temperature change into equivalent voltage signal change we use the temperature coefficient of resistivity (TCR) property of the sensor. Assuming perfect linearity of the sensor TCR (see figure below), the relationship between the sensor resistance and its temperature is given by:

$$R(T) = R_0(1 + \alpha T) = R_0 + AT \qquad (3)$$

Where R(T) is the resistance of the sensor at temperature T, R_0 is the sensor resistance at 0ºC, T is the sensor temperature (ºC), α is the TCR and *A* is the slope of resistance versus temperature.

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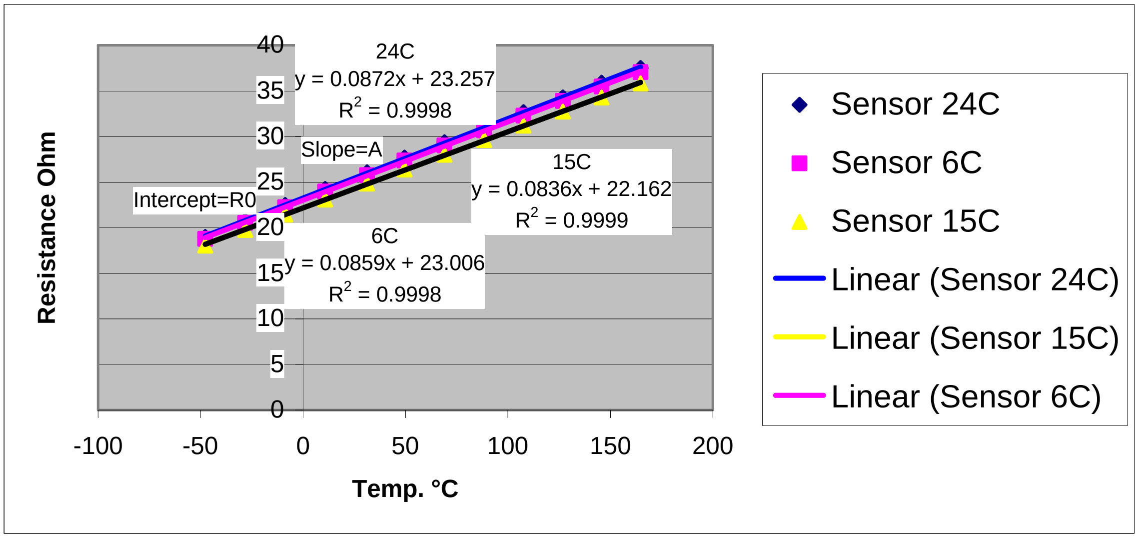

Connecting equations (2) and (3) and using $V=IR$ yields:

$$\Delta V(t) = \frac{1.1284 IAG\sqrt{t}}{e_1 + e_2} \quad (4)$$

Where I is the current supplied to the sensor.

Equation (4) can also be written as:

$$\Delta V(t) = m\sqrt{t} \quad (5)$$

Where m is the slope of the sensor voltage change versus square root of time. This holds since all the parameters on the right of equation (4) are constant during the transient.

Example of voltage versus $\sqrt{t}$ measurement is given in the next figure:

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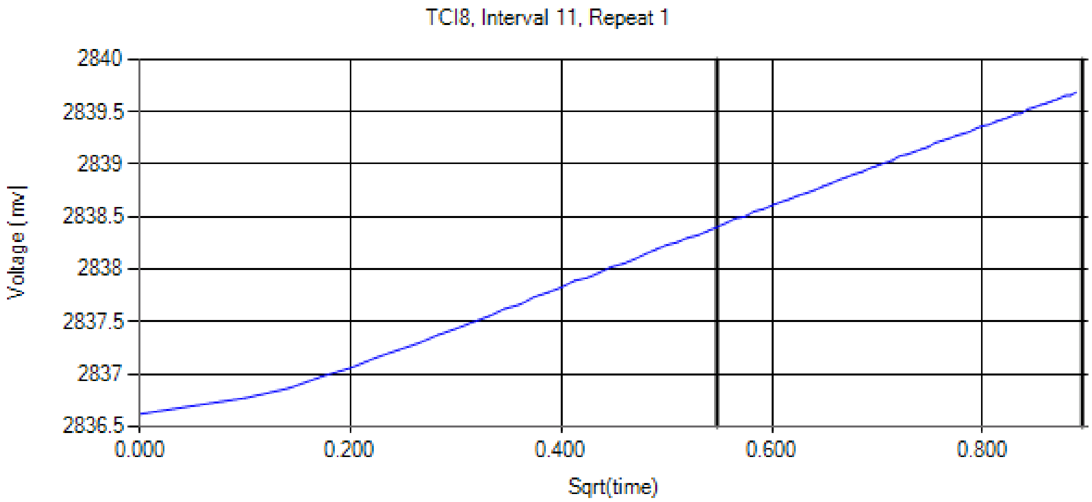

Sensor effusivity calibration

It can be shown from equations (4) and (5) that the sample effusivity, e_2, can be calculated from:

$$\frac{1}{m} = M \cdot e_2 + C \tag{6}$$

Where M is the slope of the effusivity calibration and is equal to:

$$M = \frac{1}{1.1284 I \cdot A \cdot G} \tag{7}$$

And C is:

$$C = \frac{e_1}{1.1284 I \cdot A \cdot G} \tag{8}$$

Calibration of the sensor signal against materials with known effusivity e_2 can provide the coefficients M and C in equation (6). An example of sensor effusivity calibration curve using vacuum and other materials is given below. The calibration line shows very good linearity.

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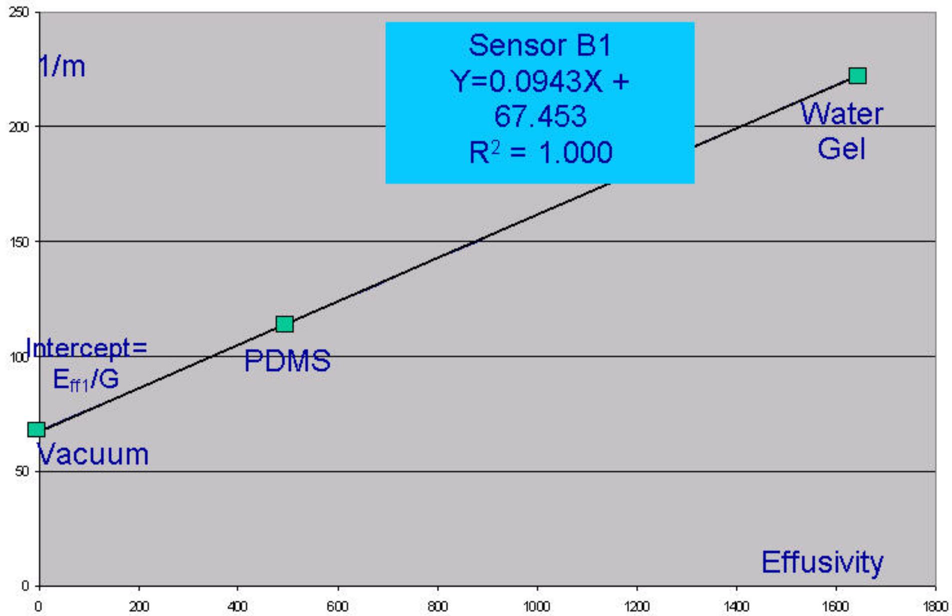

Sensor conductivity (k) calibration

Calibration and measurements of *k* are based on same data acquired for effusivity. The algorithm to calibrate and calculate *k* is the *m**, outlined in C-Therm US Patent 6,676,287 B1. It uses an iterative process to calibrate the sensor against measured materials with known thermal conductivity. The calibration process generates a value called *m**, such that:

$$\frac{1}{m - m^*} = Slope \cdot k + Intercept \qquad (9)$$

k is calculated from equation (9). An example of *k* calibration is given in the figure below.

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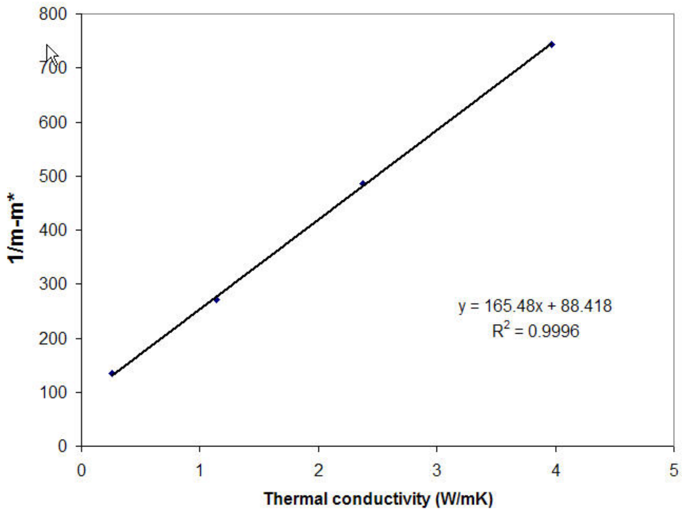

Limitations for *k* measurements

As mentioned above, the method for determining the thermal conductivity of the material is based on the effusivity measurement (see also Patent # 6,676,287**:** Direct thermal conductivity measurement technique). Therefore, different calibration curves are required for materials with dissimilar thermo physical properties. For instance, it is necessary to calibrate solids and liquids separately, and use the applicable calibration when measuring a certain material. Measuring a liquid with a calibration made for solids, or vice versa, will generate an invalid result.

Since effusivity includes k, ρ and Cp, it is possible that two different materials will have the same effusivity, but different k if their (ρCp) product is different. In such rare cases, the calculated k may be incorrect. In avoiding such circumstances, the use of the following guidelines is encouraged:

Always measure a sample with the test method that uses a calibration group which is closest to the sample's type of material.

And, use the following (ρCp) values as a guide:

Calibration	**(ρCp), 10^6 J/m^{3}K**
Liquids and powders	0 - 4.5
Foams	0 - 0.5
Polymers	1.3 - 2.0
Ceramics	2.0 - 2.7
Metals	2.4 - 4.0

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If you know the accurate (ρCp) of your sample, enter the data in the TCi software (feature available in Version 2.0) for optimizing the thermal conductivity measurement.

Material groups and power levels

The wide range of effusivity and *k* requires grouping of materials with similar behavior and effusivity/k range, and operation of the TCi sensor at different power levels. Each group of materials has its own calibration curve.

The table below summarizes the material groups and their attributes.

Material Groups	**Effusivity Range ($W\sqrt{s}/m^2K$)**	**k Range (Wm/k)**	**Temp. Range (°C)**	**Power Level**
Liquids & Powders	0-1,660	0 -0.6	$0 \le T \le 100$	Low
Foams	50-200	0.04-0.09	$0 \le T \le 60$	Low
Polymers	600-1,400	0.25-1.1	$-20 \le T \le 80$	Low
Ceramics	1,400-8,000	1.1-29	$-20 \le T \le 200$	Low
Metals	4,500-19,000	6-110	$-20 \le T \le 200$	High

Contact agent

The TCi sensor has a solid surface optimally engineered for the testing of fluids. When measuring solids a contact agent is required as there is some contact resistance that may significantly affect the results if not addressed within the measurement protocol. The quality of contact and therefore the heat transfer depends on many parameters such as type of material, surface quality and wettability.

The best contact agent available is water, since it has a relatively high thermal conductivity (~0.6 W/mK), low viscosity, and is easy to apply and clean. Water can be used in a limited temperature range though, from ~5°C to ~70°C. At temperatures lower than 5°C and higher than 70°C alternative contact agents are available. Calibrations of solids (except for foams) are all done with water.

For more information visit www.ctherm.com or contact C-Therm Technologies via email at sales@ctherm.com.