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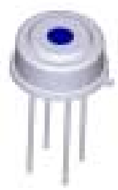
appl. note

Remote temperature measurement with PerkinElmer thermopile sensors (pyrometry): A practical guide to quantitative results



Abstract

A thermopile sensor generates a voltage, which is proportional to the incident infrared (IR) radiation power. Because every object emits IR radiation with a power, which is a strict function of its temperature, one can deduct the object's temperature from the thermopile signal. This method is called pyrometry.

PerkinElmer's thermopile sensors [1] are perfectly suited to be employed in precision devices, such as ear thermometers and pyrometers, as well as in applications like microwave ovens, air conditioners, hair dryers, etc. Because of their cost effectiveness together with their excellent performance, such as long term stability and a very low temperature coefficient of sensitivity, millions of these devices have found their way into high volume applications, making PerkinElmer the leading thermopile manufacturer in the world.

This brief application note aims at a better understanding of the use of PerkinElmer's thermopile sensors in temperature sensing and measurement. The focus here is on the quantitative analysis of the signals and the principle of the calibration procedures. The paper starts with a review of the physical picture of the heat balance equations, continues with the introduction of an analog temperature compensation procedure, and will finally focus on the more precise method of employing numerical means. Special attention is given to the discussion of measurement errors and achievable accuracy.

If there are any questions you encountered, please do not hesitate to contact the author by e-mail: juergen.Schilz@perkinelmer.com .

Contents

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1 The heat balance equation

The total radiation power P_{obj} emitted by an object of temperature T_{obj} can be expressed as

$$P_{obj} = \sigma \cdot \varepsilon \cdot T_{obj}^4 , \quad (1)$$

with σ being the Stefan-Boltzmann constant and ε the so-called emission factor (or emissivity) of the object in question. In the ideal case ε has the value 1 – then we speak of a black-body. For most substances the emission factor lies in the range between 0.85 to 0.95. Equ. (1) is called the Stefan-Boltzmann law. It sums up (integrates) the total quantity of radiation over all wavelength. If you are interested to gain a deeper understanding of the IR radiation physics, I recommend you to look into suitable physics books under “black-body radiation”. Here, we will not go deeper into it.

We can now use one of the PerkinElmer thermopile sensors, to measure the heat radiation according to Equ. (1). Well, this is not as straight forward as it might look at the beginning. First of all, we needed to introduce into Equ. (1) something about the sensing geometry; especially the sensing angle. Second, we need to take into account the temperature of the thermopile itself (i.e. the instrument or the ambient temperature), because also the thermopile itself emits heat following Equ. (1).

This leads us to the heat-*balance* equation, which relates the *net* power P_{rad} received by the thermopile to the two temperatures T_{obj}, in which we are actually interested in, and to the temperature of the instrument itself. Since in most cases the instrument’s temperature equals (or is near to) the temperature of the ambient, we will refer this value to T_a, the ambient temperature.

Therefore the total heat power P_{rad} received from the object at temperature T_{obj} is given to

$$P_{rad} = K' \cdot \left(\varepsilon_{obj} T_{obj}^4 - \varepsilon_{sens} T_a^4 \right) \quad (2)$$

In Equ. (2) we changed from the physical constant σ to an empirical factor K' which we call the instrument factor. K' contains of cause the constant σ in some form, but it mainly includes the view angle or field-of-view (FOV) of the thermopile instrument. The FOV is marked by the Greek letter φ and it is explained in Fig. 1.

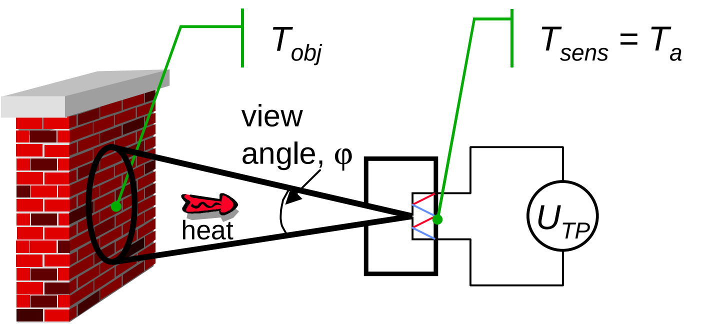

Figure 1: The definition of the field of view (FOV) or the view angle, φ.

φ is the angular measure of the cone opening from which the sensor receives radiation. One can now show that the instrument factor K' can be written as $K' = K \cdot \sin(\varphi / 2)$ [2] and thus the total received radiation power amounts to

$$P_{rad} = K \cdot \left(\varepsilon_{obj} T_{obj}^4 - \varepsilon_{sens} T_a^4\right) \cdot \sin^2(\varphi/2). \qquad (2a)$$

The thermopile sensor is an instrument, which generates a voltage U_{TP}, which is proportional to the incident net radiation, P_{rad}. The proportionality constant is the so-called sensitivity S. Therefore, one arrives at the following equation

$$U_{TP} = S \cdot P_{rad} = S \cdot K \cdot \left(\varepsilon_{obj} T_{obj}^4 - \varepsilon_{sens} T_a^4\right) \cdot \sin^2(\varphi/2). \qquad (3)$$

Equ. (3) is the fundamental and correct relationship that tells us the output voltage as a function of the object (and ambient) temperature. For a fixed ambient, the output voltage of the thermopile is proportional to T_{obj}^4. This is however only valid, if the sensor senses the whole electromagnetic spectrum with the same sensitivity! (Remember that Equ. (1) is already an integral.) Since in all practical situations one never senses over all wavelengths – for example most PerkinElmer thermopiles have a built-in 5.5 µm infrared longpass – the pure T^4 dependence will rarely be seen, or it will only be an approximation for restricted temperature ranges.

What the exact curve is, depends on several factors, such as the object temperature range in question and the spectral characteristics of the instrument response. The thermopile itself senses radiation from about 1 to over 20 µm with a constant sensitivity, but any lens, mirror, or filter in the optical path changes the response characteristics. To show the deviation from the physical T^4 law, we will here introduce a deviation constant δ to make the temperature dependence a $T^{4-\delta}$ law.

Additionally, to facilitate the further analysis, we will melt the two emission factors ε_{obj} and ε_{sens} into one effective constant ε. Thus Equ. (3) will read:

$$U_{TP} = S \cdot K \cdot \varepsilon \cdot \left(T_{obj}^{4-\delta} - T_a^{4-\delta}\right) \cdot \sin^2(\varphi/2). \qquad (3a)$$

Equ. (3a) is indeed based on a physical analytical approach, but it already contains empirical factors, which are needed to be determined in order to attribute to the practical reality. What the exact temperature dependence is, whether it really can be described by $T^{4-\delta}$ or whether it needs a more complicated formula, needs in fact to be individually determined for every application. The direct approach to this is experimentally by performing precise measurements and looking for an empirical fit to derive a relationship of thermopile output voltage and object temperature. If a micro controller is used, the values will then mostly be listed in the form of a look-up table. In this case no explicit analytical formula is needed.

2 Ambient temperature compensation

For a fixed ambient temperature, any empirical fit of U_{TP} versus T_{obj} or any look-up table will give the correct result. From device to device a single proportionality constant is then sufficient as calibration factor. However, as seen from Equ. (3a), the output signal will vary, when the ambient temperature changes. Any IR temperate measurement system needs therefore to compensate this effect – i.e. a so-called ambient temperature compensation needs to be implemented to make sure that the instrument determines an object temperature value, that is independent from the sensor temperature itself.

In many industrial applications the ambient temperature compensation of the output signal is achieved by employing an analog circuit. The circuit is designed in a way, that a voltage is generated, which matches exactly the loss or gain in output voltage due to any ambient temperature change. This method, which is also employed in the PerkinElmer thermopile module TPM is explained in paragraph 3.

For high accuracy applications, as needed for ear thermometers or precision pyrometers, a digital (numerical) calculation method is needed. The principle how to perform this, is explained in section 4.

3 Analog solution

The Figure 2 shows the principle as it is employed the PerkinElmer thermopile module TPM, which is already in use in millions of microwave ovens, air conditioners, and numerous other consumer applications.

The thermopile output follows the already known law according Equ. (3a). Because thermopile signals are usually in the range of millivolts, they need amplification by a very low noise and low offset operational amplifier (OpAmp). The output signal simply multiplies by the amplification factor *A*.

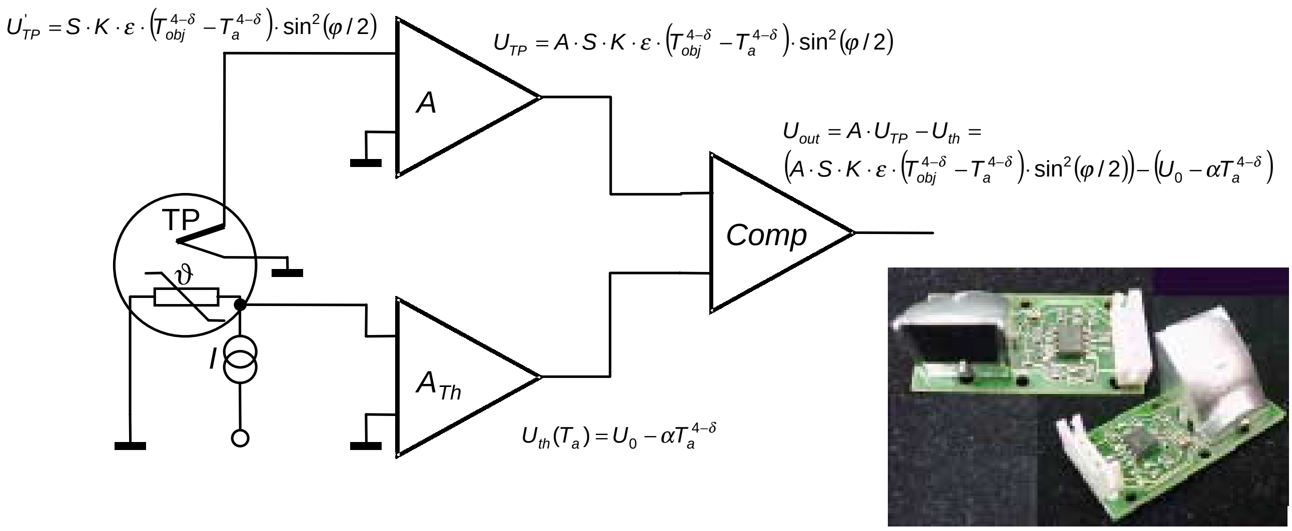

Figure 2: Schematic of the pyrometer circuit with analog ambient temperature compensation as employed in the PerkinElmer thermopile module TPM. The inset shows a photo of the module TPML1 which operates as temperature controller in e.g. microwave ovens.

For the ambient temperature compensation, the internal thermistor is used, which sits in the thermopile housing and therefore records exactly the sensor's temperature. The thermistor has an NTC behavior with a non-linear resistance vs. temperature characteristics. It is well known that the best fit to the resistance-temperature function $R(T_a)$ is achieved by using an exponential equation, but for a limited temperature range one can approximate the thermistor's $R(T_a)$ behavior by a T^4 (or of course also by a $T^{4-\delta}$) law of the form

$$R(T_a) = R_0 - \varsigma T_a^{4-\delta}, \qquad (4)$$

with ζ being a proportionality factor and R_0 a constant. A constant (but small) electrical current through the thermistor generates concomitantly a voltage, which is subsequently amplified by a factor A_{Th} to amount to U_{th}. This voltage is proportional to *R*:

$$U_{th}(T_a) = U_0 - \alpha T_a^{4-\delta}. \qquad (4a)$$

This voltage is added to the thermopile signal by means of a second operational amplifier as seen in the Figure 2. This amplifier is called the compensation stage. The resulting voltage at the output of that stage is then

$$U_{out} = A \cdot U_{TP} - U_{th} = A \cdot S \cdot K \cdot \varepsilon \cdot \left(T_{obj}^{4-\delta} - T_a^{4-\delta}\right) \cdot \sin^2(\varphi/2) - \left(U_0 - \alpha T_a^{4-\delta}\right). \qquad (5)$$

The desired ambient temperature compensation is achieved, if the output, i.e. Equ. (5) is independent of the ambient temperature T_a. This means that the two terms containing T_a, must cancel out, i.e. the following relation must be fulfilled:

$$\alpha - ASK\varepsilon \sin^2(\varphi/2) = 0. \qquad (6)$$

The adjustment of the compensation of the module is performed by regulating the amplification of the first stage. According to Equ. (6) this amplification factor amounts to

$$A = \frac{\alpha}{SK\varepsilon \sin^2(\varphi/2)}\,. \qquad (7)$$

Equ. (7) is worth a closer look. The adjustment of the amplification of the thermopile stage is not only due to the thermopile sensitivity *S* as one would of course imagine, but also on both the field-of-view of the sensor and the emission factor of the object to be sensed! This means that, if you get a calibrated PerkinElmer thermopile module TPM, you are not allowed to bring any additional filter or aperture into the optical path, since then not only the output curve will change its value, but also the ambient temperature compensation will be gone. The module is usually calibrated and the ambient temperature compensation is set for a certain optics and an emission coefficient of 0.95, which covers most applications.

Two remarks here, before we continue with the digital version:

- Of course it is possible to adjust the amplification stage to your special application, where you need to sense an object with different emission factor, or have the requirement to put any additional filter or aperture into the optical path. The thermopile application team of PerkinElmer in Wiesbaden, Germany, is happy to perform the necessary measurements and calculations for you and deliver a device that perfectly suits your application. These actions need, however, to be reimbursed if your application runs only in low volumes ☹.
- Please do not employ the analog temperature compensation for any application that requires a high accuracy, namely ear thermometers or precision pyrometers. Because the two functions, thermopile output and thermistor curve, that have to be added, do not have exactly the same functional behavior, the deviations are too large to meet international standards for e.g. medical devices. The analog version can hardly deliver an absolute accuracy better than ±4 °C. This is indeed sufficient for the majority of consumer applications and industrial regulating devices, but not for an instrument, where an absolute value has to be deducted in a range better than 0.1 °C.

4 Digital solution

In the last section it became clear that one of the main factors that determine the accuracy of a thermopile based pyrometer device is the ambient temperature compensation. The analog solution presented is indeed at very low costs, but lacks of absolute accuracy. For precision devices it is therefore needed to employ a numerical method which allows the addition of a compensation value which fits exactly to the signal change.

For this purpose, the two signals, thermopile voltage and thermistor resistance (voltage) are derived separately and fed into an analog-digital (A/D) converter. The A/D transfers the values into a micro controller system, where the necessary calculations are made. The calculated temperature output can then either be presented in digital form or it will be fed into a digital-analog converter stage that delivers a linearized signal. The principle circuit is shown in Fig. 3.

If you look at Equ. (3a) again, it seems that it is necessary to feed a two-dimensional field of U_{TP} versus T_{obj} and T_a into the micro controller to make the computer able to derive the object's temperature at any possible ambient condition. Fortunately, by analyzing the structure of the equation, we can come to a much simpler solution. In fact, only two one-dimensional look-up tables are necessary: One for the thermopile voltage U_{TP} versus T_{obj} at a fixed ambient temperature T_{ref}, and one table for the thermistor resistance (or thermistor voltage) versus the ambient temperature T_a.

To see this, we will change the notation of the formulas from the physical (analytical) picture to a more abstract way. In general it is not necessary to know the exact functional behavior of U_{TP} versus T_{obj} and T_a, – it is only important to know about the following *property* of the functional behavior. The heat balance equation can generally be written as

$$U_{TP} = K \cdot f(T_{obj}, T_a)\,. \tag{8}$$

The function *f* does not need to be known in an explicit way. Important to know is the expansion property of the heat balance equation as follows:

$$U_{TP} = K \cdot f(T_{obj}, T_{ref}) - K \cdot f(T_a, T_{ref})\,, \tag{9}$$

with T_{ref} being an arbitrary fixed temperature, e.g. 0°C. Now we can work with a single look-up table, where we list $f(T, T_{ref})$. For a measurement, this table is now used twice: first the correction term $f(T_a, T_{ref})$ is obtained, by using T_a as look-up parameter and then T_{obj} is derived by looking into the same table in reverse direction.

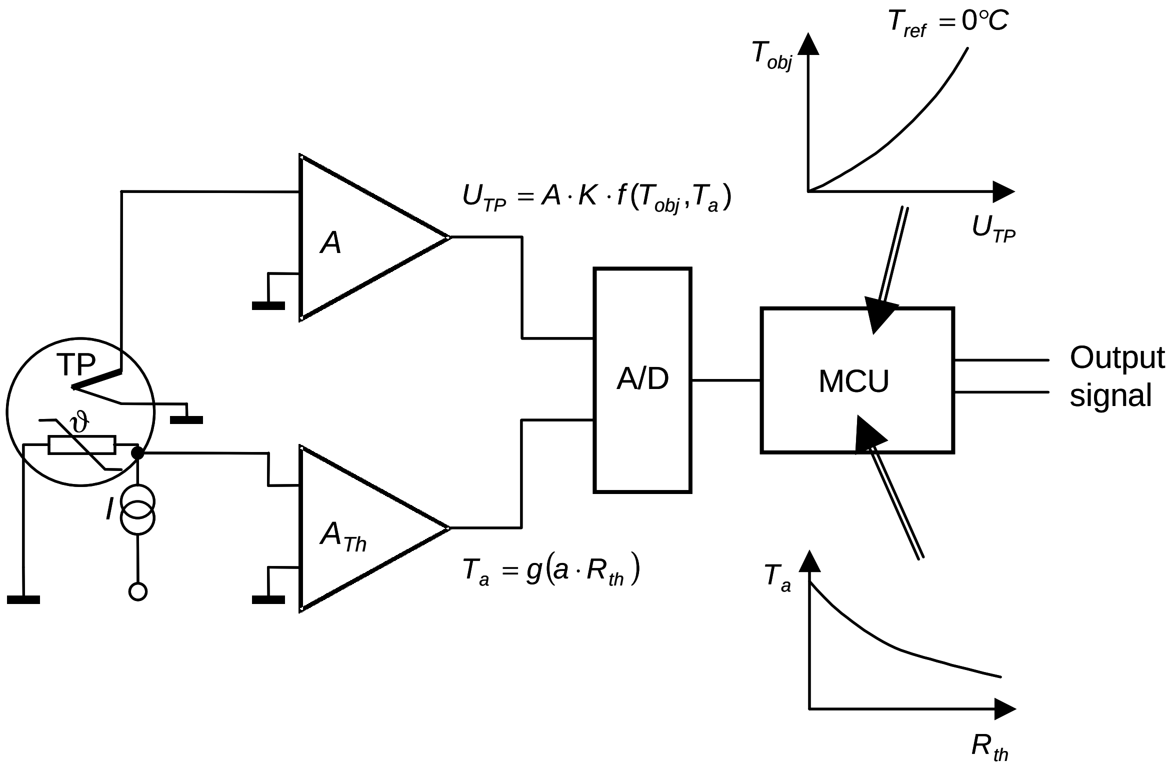

Figure 3: Schematic of a micro controller based pyrometer circuit with numerical ambient temperature compensation.

4.1 The measurement procedure

To be more specific, the measurement procedure will be listed here step by step, where it is assumed, that the calibration factors are already known. We will deal with the calibration procedure in the next paragraph.

Step 1:

Measure the thermistor resistance R_{th} via the thermistor voltage U_{th}. Then derive the ambient temperature from the thermistor value R_{th}. The necessary function $g(R_{th})$ is listed in a look-up table, from which T_a is derived by multiplying R_{th} with the calibration factor *a*:

$$T_a = g(a \cdot R_{th})\,. \tag{10}$$

Step 2:

With T_a now known, obtain the ambient temperature compensation term $f(T_a, T_{ref})$.

Step 3:

Now you can get the object temperature by reverse looking in $f(T, T_{ref})$:

$$f(T_{obj}, T_{ref}) = \frac{U_{TP}}{K} + f(T_a, T_{ref}) \Rightarrow T_{obj} \ . \qquad (11)$$

This method can be very accurate if the calibration factors *a* and *K* are known. How to obtain these is subject of the following section.

4.2 The calibration procedure

4.2.1 Thermistor

A thermistor is characterized by two parameters: first the so-called β-value and second by an absolute resistivity value at a fixed temperature – mostly at 25°C. For example, the two different thermistors which are employed in the various PerkinElmer thermopile sensors have nominal values of 30 kΩ and 100 kΩ at 25°C, respectively. Since the materials of these two thermistors are identical, their β-values are equal. In practice, the nominal value at 25°C and also the β-value have a certain variation from both their specified value and from device to device. For example, the nominal value may vary ±5%, which is an error resulting mainly from geometrical deviations. The β-value varies typically around 1% – this error is a result of structural and/or composition deviations, i.e. material properties.

For the typical ambient temperature which is of interest, e.g. 10 to 45°C, the β-value is often assumed to be a constant and will therefore not calibrated, i.e. adjusted to fit the individual thermistor curve. The deviation from the absolute value, however, is mostly significant and has to be calibrated. With the nominal thermistor curve R_{th} versus T_a called $g(R_{th})$, one can adjust this curve by a multiplication factor *a* to fit the nominal (tabulated) value. This is shown in Equ. (10). The parameter *a* is obtained by measuring the thermistor resistance at a fixed and stable, well known ambient temperature, e.g. within an extremely good thermostatized chamber or room and then comparing with the nominal value.

The lookup table then contains the nominal thermistor values in e.g. steps of 2.56°C or 1.28°C, dependent, what absolute accuracy is needed. By a linear interpolation in a table with 2.56°C spacing, it should be possible to achieve an accuracy better than 0.3°C. This can easily be seen by comparing the linearized value with the nominal one. For the PerkinElmer thermistors, tabulated values are obtainable on request.

One remark at last: Before being able to calibrate for a thermistor value deviation, it is of course necessary to calibrate each device with a known resistor and/or voltage to be sure to measure the right thermistor resistance.

4.2.2 Instrument factor (thermopile)

The instrument factor *K* contains all device variations in thermopile sensitivity and view angle. If the overall response characteristics of the thermopile stays constant – and that is mostly the case, since small deviations in the filter properties do virtually not affect the integrated signal – one can store an experimentally derived lookup table for the thermopile values, i.e. $f(T, T_{ref})$ for the object temperature range in question.

The calibration will now be performed at a fixed ambient temperature T_a. The thermopile will be shown two black bodies at different temperatures T_1 and T_2. This results in the two output voltages:

$$U_1 = K \cdot (f(T_1, T_{ref}) - f(T_a, T_{ref})) \text{ and} \qquad (12a)$$

$$U_2 = K \cdot (f(T_2, T_{ref}) - f(T_a, T_{ref})) \qquad (12b)$$

By subtracting these two equations, (12a) and (12b), one can eliminate the constant term $f(T_a, T_{ref})$ and thus calculate the instrument factor *K*. After these two calibration steps, the device is ready for a measurement. For the final test a check of the right calibration should be performed with a third blackbody at another temperature.

Remark: This way of calibration assumes that the sensitivity of the thermopile and concomitantly the instrument factor *K* is not a function of the ambient temperature! For the PerkinElmer thermopiles made by CMOS compatible Si-technology and not containing Bi-Sb alloys, the sensitivity *S* varies only about 0.02%/K, which is virtually constant over the ambient range of interest.

5 Conclusions

This short paper could of course not cover all the details regarding your special application of remote temperature measurement (pyrometry) by using PerkinElmer thermopiles. We hope, however, that we could give you the necessary hints to bring your project to a successful ending. If there are any data necessary for your application, please do not hesitate to contact us. Well, we are not able to take your development part, but the application team at PerkinElmer Wiesbaden is happy to give you the necessary (and hopeful useful) advice.

For the analog solution, the PerkinElmer thermopile modules come readily calibrated to be plugged in into the application. For the digital solution PerkinElmer can offer an instrumentation amplifier that includes a multiplexer, a low-noise operational amplifier, a 14 bit A/D converter, an 8 bit micro controller, digital input/output ports, which may already come in module form combined with one of our thermopile sensors to form a digital pyrometer.

6 Literature

[1] J. Schilz, thermophysica minima: thermoelectric infrared sensors (thermopiles) for remote temperature measurements; pyrometry, PerkinElmer Optoelectronics.

[2] see e.g.: W.J. Smith; *Modern Optical Engineering, The design of Optical Systems,* Optical and Electro-Optical Engineering Series, Eds: R.E. Fischer & W.J. Smith, Mc Graw Hill 1990.