THERMOELECTRIC INFRARED SENSORS (THERMOPILES) FOR REMOTE TEMPERATURE MEASUREMENTS; PYROMETRY

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Abstract
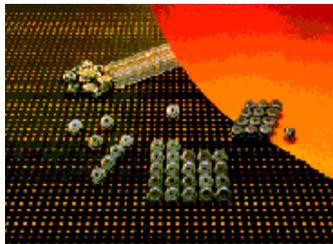
Nowadays, there are thermopile sensors available, which allow remote temperature sensing at quite low overall system costs. The sensor does not require any cooling and – dependent on the measurement range – can reach a typical accuracy of ±1 K. For narrow temperature ranges as e.g. in body temperature measurement, a precision of 0.1 K is possible.

PerkinElmer Optoelectronics has developed a series of thermopile types adapted for various applications. Available standard devices are:

⮑ sensors for ear thermometers to sense body temperature,

⮑ sensors with focussing optics and signal processing electronics (on circuit board or integrated in sensor housing) for object temperature control in microwave ovens, hair dryers, cookers, etc.,

⮑ sensor arrays with integrated multiplexer and amplifier for pattern recognition in position control in e.g. automobiles (airbag safety), room sensing by position and direction control of humans, etc.

⮑ sensors with infrared bandpass filters for gas detection by infrared absorption. This subject is covered by a separate article [1].

The achievement of a good performance of thermopile devices requires a minimum of knowledge on infrared technology and thermal management of thermoelectric devices. This article therefore aims at the necessary basics for a correct implementation.

1 Introduction

Every object emits radiation which is largely controlled by the object's temperature. For an object that has "no color", which means, no wavelength is selectively emitted or absorbed, the radiation spectrum is completely determined by the temperature alone. In this case, one speaks of a "black body". The spectral radiation characteristics of a black body can be theoretically calculated. Figure 1 shows them for selected temperatures.
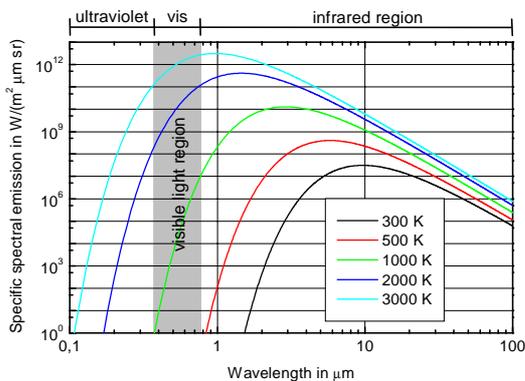
Figure 1: Spectral radiation characteristics of a "black body" at different temperatures (Planck's radiation law). It is to be noted that the curves never intersect, which means that the radiation intensity at every wavelength is a strict function of the temperature. By measuring the intensity of the radiation one can therefore determine the object's temperature.

With rising temperature, the intensity at every wavelength of the radiation spectrum increases as well. This means that one can remotely determine the temperature of an object by measuring its radiated power. Such a measurement can, for example, be carried out by using your eyes. The human eye is sensitive for radiation in the range from 0.38 to 0.75 µm. This region – it is naturally called the "visible spectrum" – is marked in Figure 1. If the temperature of an object exceeds 400 °C (700 K), it will emit a remarkable portion of radiation at the red end of the visible region. It will start to glow in a dark red color, an effect well known from electrically heated stoves. When further increasing the temperature – lets say to 1000 °C (1300 K), the glowing will not only become more intensive, but also its color will change to light red, because there are now green and yellow portions added. Radiation from an object with a temperature of 6000 K will appear as bright white for our eyes. 6000 K is the

temperature of the sun and our eyes are adapted to "detect" this radiation as white light.

1.1 Photonic detectors

If the measured body has a temperature lower than 400 °C, one needs a radiation detector which is sensitive to a much longer wavelength than those of the visible spectrum. A detector is needed, which is sensitive to the infrared region (also called heat radiation) around 10 µm wavelength. There are different sensors available, which are capable for accurately detecting and measuring heat radiation in the 3 to 20 µm infrared (IR) wavelength region. The most common IR detectors employed during the past decades are based on semiconductors, in which the incident IR radiation induces a change in electrical conductivity, which can easily be measured and used as the sensing signal for the incident power. Such photonic detector systems offer a great accuracy and sensitivity to IR radiation. The needed semiconductors and thermal and electrical systems, though, are very expensive.

Thermal facts

There are people who think that an infrared temperature measurement needs to *send out* some sort of radiation which may be harmful. Therefore they hesitate to use an ear thermometer, for example.

It thus has to be emphasized that a radiative temperature measurement is an entirely *passive method* – it measures only the natural heat which is sent out by every object.

1.2 Pyroelectric sensors

For a long time the high cost issue posed severe constraints on the development of IR systems for the consumer market. This could only be overcome by another class of detectors. A type of sensor capable to detect IR radiation with a good accuracy and at the same time being available at low cost are the so-called pyroelectric sensors. Here, the heat radiation collected by the pyroelectric material generates a static voltage signal across the crystalline material. Under constant illumination, however, the signal declines, which makes a periodical refresh necessary. This is usually achieved by a

usually achieved by a mechanical chopper in front of the detector.

Pyroelectric detectors are applicable for mass production. They have found their way into the consumer market through applications in burglar alarm systems and automatic light switches. Here, the detector senses the IR radiation from approaching persons. In this case, no chopper is needed, because an optics focuses the radiation from the moving persons alternately onto two detector crystals with opposite polarity. This generates a difference signal, which drives a switch or an alarm. The advantage of pyroelectric detectors is in detecting moving objects and at the same time suppressing quasi-static signals as from furnaces and other heat sources, which vary only slowly in time. On the other hand, for static temperature measurements one still needs a relatively expensive setup which includes mechanical parts.

1.3 Thermopile sensors

Recently, an over 150 year old method to measure infrared radiation is revived: The utilization of thermocouples. A thermocouple consists of two different materials which are connected at one end, while the other two ends are attached to a voltage meter (cf. Figure 2a). If there is a temperature difference between the common junction and the voltmeter ends, a so-called thermovoltage is shown by the meter. The magnitude of the voltage is a function of the temperature difference, but also dependent on the nature of the two employed materials.

If we now attach an absorber to the junction, and place it into the IR radiation coming from an object, the absorber will collect the incident heat (Figure 2b). We can simply say that the absorber and thus the thermocouple junction will warm up due to the incident radiation. After a short while, the temperature difference between the (warm) junction and the (colder) reference ends will stabilize. The thermocouple material in turn converts the temperature difference into a voltage shown by the voltmeter. Thus, the voltmeter reading is a direct measure for the object temperature. This method is principally simple, does not need any mechanics, and can accurately sense static signals. Like the pyroelectric detectors, a thermopile sensor generates the measurement signal by itself, not requiring any current source.
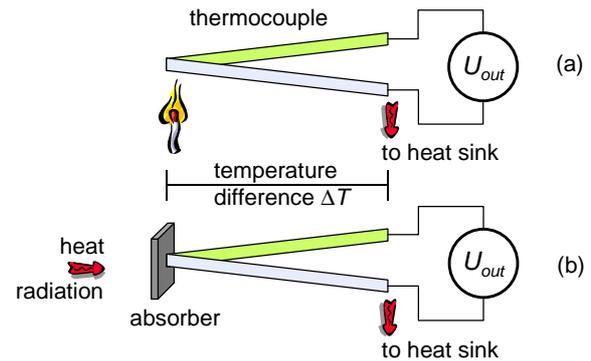
Figure 2: Thermocouple principle. (a) Two dissimilar conductors form a thermocouple. A temperature difference over the couple generates an electrical voltage. (b) The needed temperature difference emerges if heat is absorbed by the thermocouple junction and led to a heat sink. The developing voltage is proportional to the amount of flowing heat.

Classically, several ten macroscopic wire thermoelements were connected in series in order to increase the generated voltage and to make the system more sensitive. The materials employed were mostly antimony and bismuth, as they exhibit a large thermovoltage. The resulting system was called a thermopile, because it was indeed a pile, made of a large heavy block. Figure 3 shows an original sketch of such an instrument after N. Nobili (1835). Due to the large thermal masses it was very slow in following signal changes. As can be imagined, these instruments were originally only applicable for laboratory work.
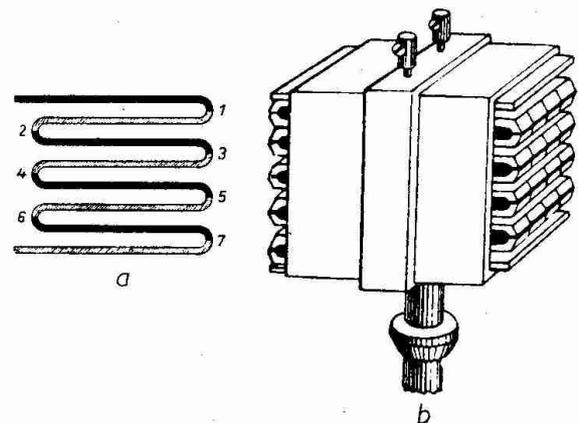
Figure 3: In series connected thermocouples made of antimony and bismuth (a) form a thermopile (b). After N. Nobili (1835).

Nowadays, modern semiconductor technology makes it possible to produce thermopile sensors consisting of hundreds of thermocouples on an area of several square millimeters. Such a sensor is extremely sensitive, shows a very fast response

time due to its smallness, and it is additionally inexpensive, because of the employment of semiconductor mass production means. PerkinElmer, who is well known for many years for its pyroelectric detectors, has developed a unique technology to produce thermopile sensors and arrays by means of silicon micromachining. Due to the automated batch processing, the sensors offer a high reproducibility and accurateness. Its compact size makes them very robust and easy to operate.

2 Thermopiles by modern microsystem technology

Figure 4 shows a sketch of the architecture of a micromachined thermopile chip and Figure 5 shows a photo. The production occurs first by deposition of a thin glassy (electrically insulating) layer onto a silicon wafer. Up to a hundred thermocouples together with their connecting leads are subsequently deposited. Depending on the wafer size, one disk can carry several thousand elements. The processed wafer undergoes a micromaching step, where the silicon below the membrane is removed by an appropriate etching process. The last step is the deposition of an absorber material, which shows a high and constant absorption coefficient in the considered IR region [2].
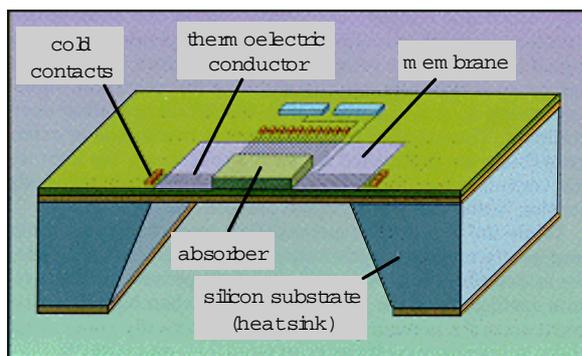
Figure 4: Sketch of a micromachined thermopile. The thermocouples made of silicon and aluminium are placed between the center of a thin membrane and a silicon rim. The membrane has a high thermal resistivity and thus allows the center junctions to raise their temperature when IR heat radiation hits the absorber layer. The resulting temperature difference between the absorber and the rim is converted into a voltage, which can be measured at the sensor's output leads.

The elements on the wafer are separated by cutting and then bonded into a standard (transistor outline, TO) housing (cf. Figure 5). A cap with an infrared window is welded onto the base plate

in inert atmosphere. These single elements are the simplest form of micromachined thermopiles. Figure 6 shows an arrangement of them. More complex forms involve line or array arrangements (cf. Figure 7) [3].
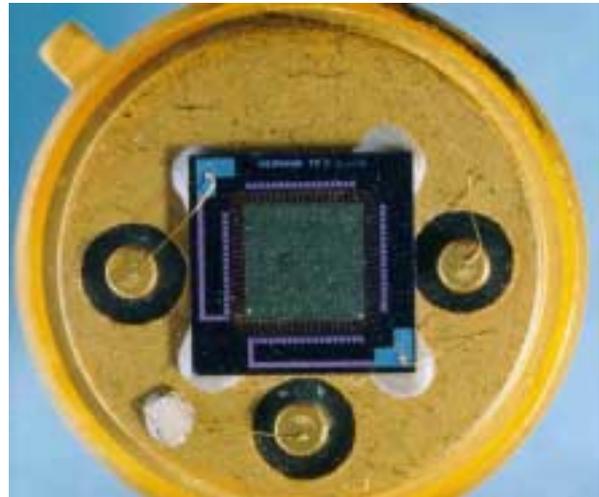
Figure 5: PerkinElmer micromachined thermopile on a transistor housing base plate. The thermocouple's cold contacts can clearly be seen on the silicon rim. The center square is the absorber layer. The output leads are bonded to the left and right connection pins. The lower pin is connected to the thermistor, which can be seen in the lower left corner.
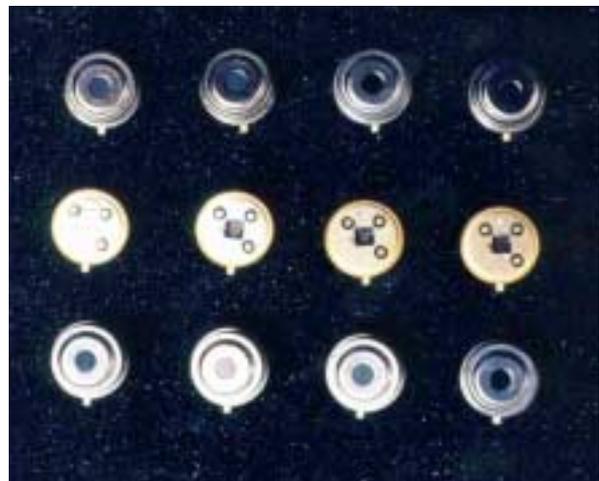
Figure 6: Thermopile sensors: The upper and the lower rows are sensors in TO housings sealed under inert atmosphere. The round hole is the infrared window, through which the radiation reaches the absorber.

The output signal of a thermopile sensor is in the submillivolt range and has to be amplified for further processing. The amplifier for this purpose should be placed as close as possible to the sensor in order to maintain a good signal-to-noise level. The latest sensor generations therefore feature an application specific integrated circuit

(ASIC) placed together with the sensor into the housing. Arrays have additionally a multiplexer which reads the pixels in a series. This holds connection wires to a minimum.
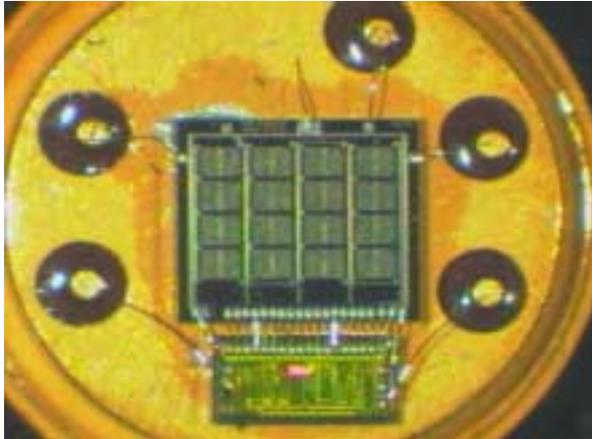
Figure 7a: 4x4 thermopile array with integrated circuit (ASIC) containing the multiplexer and amplifier.

Figure 7b: Thermopile line array with ASIC containing the multiplexer and amplifier. The right side shows the capped sensor with micromachined silicon lens.

Thus today's integrated circuit processing technology is able to produce thermopile devices which are smaller, perform better and are less costly than traditional sensors.

3 Characteristic figures of thermopiles

Sensitivity:

The most important parameter of a thermopile sensor is its sensitivity, S, often also called responsivity. It connects the voltage output of a sensor, U_{out}, to the absorbed radiation power, P_{rad}. Its definition is therefore

$$S = \frac{U_{out}}{P_{rad}}$$

with the dimension V/W. It should be as high as possible. Typical sensitivity values of thermopiles are several 10 to about 100 V/W dependent

on the area of the absorber and the number and type of thermocouples.

If the sensitivity is measured with a black body as source, it is termed *black body sensitivity*, while the term *spectral sensitivity* is used if there are filters in the radiation path. Therefore one has to carefully consider the specific circumstances when interpreting and comparing sensitivity values in datasheets.

Thermopower:

The incident radiation power generates a temperature difference, ΔT, between the warm and cool ends of the individual thermocouples. This in turn gives rise to the mentioned thermovoltage.

Thermal facts
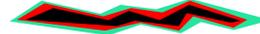
The sensitivity S is certainly the most important parameter for thermopile characterization. The higher the better and for a given thermopile the output signal directly scales with S.

But it is dangerous to use the sensitivity to rate the expected output voltage of different thermopiles. If the areas of the two devices' absorbers are different, the smaller thermopile will collect less heat radiation and hence its output signal will be smaller.

Since this is a physical fact, one has therefore carefully to *consider both*, absorber size and sensitivity.

The magnitude of the voltage in respect to the temperature difference is called the total thermopower

$$\alpha = \frac{U_{out}}{\Delta T}.$$

It is measured in V/K. A typical value of a single thermocouple made of Si and Al is 250 µV/K. A thermopile with 50 elements therefore generates 12.5 mV/K.

Noise equivalent power (NEP):

The output signal of every electric circuit and therefore of every sensor is distorted by electric noise. The largest noise source for the devices considered here is the stochastic (white) noise generated in an ohmic resistor due to charge fluc-

Thermal facts

On the design of thermopiles

It is correct that the sensitivity S becomes larger when rising the thermopower α. It is also correct that the thermopower rises when increasing the number of thermocouples. But it is **not correct** that the sensitivity inevitably rises, when increasing the number of thermocouples. Thus, a thermopile featuring 100 couples is not necessarily "better" than one with only 50 couples.

This sounds contradicting, but in fact the situation is a bit complex. The sensitivity is a function of a parameter, Z, which is expressed as $\alpha^2/(R\,K)$. Here, α is the already known thermopower, R the electrical resistance of the thermopile, i.e. the sum in resistance of all thermocouples in series, and K the thermal conductance of the thermopile/membrane system. Z is called figure-of-merit and it is the correct parameter to value the performance of a thermopile system.

The three components of Z show a mutual dependence. For example, when increasing the number of thermocouples, α will rise, but concomitantly also R, and, because adding material onto the membrane, also K will increase. It is of no use, to make the thermocouple lines simply wider or narrower, since this has either an adverse effect on K or R. Only the combination of the three parameters in the form of Z gives a valid performance value.

It has even been noted, that this discussion only covers the effect on sensitivity – not to speak from the influence of e.g. the resistivity on noise and on amplifier bias current.

PerkinElmer Optoelectronics designs its thermopiles by simultaneously taking all relevant parameters into careful consideration. Powerful layout and simulation tools guarantee that the best combination of thermocouple number, their width and length, the amount of dopants, the size and thickness of the membrane and many more parameters are chosen.

This assures that all PerkinElmer thermopiles show a good performance – which is, however, distinct for every design.

makes the charge carriers move back and forth. The average noise voltage, U_{noise}, generated at the lead outputs of a sensor is proportional to the square root of the sensor's resistance, R_{sens}, and the temperature, T. In particular:

$$U_{noise} = \sqrt{4 k_B T \cdot R_{sens} B},$$

with k_B being the Boltzmann constant and B the considered bandwidth which is usually determined by the measuring device. To become independent from the measuring method, the noise voltage is normalized by $\sqrt{B}$ and therefore given in V/Hz$^{1/2}$. In this case the symbol u_{noise} (with lower case u) is used.

Signal voltages below the noise values cannot be resolved. The incident radiation has to provide an output voltage which has at least the value of the noise. This minimum resolvable radiation power is called noise equivalent power (*NEP*) and is given by

$$NEP = \frac{u_{noise}}{S}.$$

It is measured in W/Hz$^{1/2}$. The PerkinElmer thermopiles show a typical *NEP* of 0.3 nW/Hz$^{1/2}$.

Detectivity:

There are cases where not the *NEP* is given as the characteristic figure, but its reciprocal value $1/NEP$. This is called detectivity, D, and it is measured in Hz$^{1/2}$/W.

Specific detectivity:

The parameter *NEP* and hence the detectivity depends on the area A_D of the specific detector. There is usually a square root dependence on the detector area. To be able to compare different sensor types, the detectivity is therefore normalized by $A_D^{1/2}$ defining a specific detectivity, D^*, by

$$D^* = \frac{\sqrt{A_D}}{NEP} = \frac{S\sqrt{A_D B}}{U_{noise}}.$$

It is measured in $\mathrm{cm} \cdot \sqrt{\mathrm{Hz}}\,/\,\mathrm{W}$. Representative D^*-values for thermopile sensors are $1 \cdot 10^8$ to $3 \cdot 10^8$ $\mathrm{cm} \cdot \sqrt{\mathrm{Hz}}\,/\,\mathrm{W}$.

Response time:

When receiving radiation, the detector system needs a certain amount of time to come to a

tuations within the conductor. The temperature

thermal equilibrium. The characteristic time to reach this state is called the response time or time constant of the detector. It depends on the sensor geometry and thermal properties of the sensor materials. Typical response times for micro-machined sensors are in the ten millisecond range.

4   Temperature measurements by thermopiles

As already mentioned, a thermopile sensor can be an instrument to remotely measure the temperature of objects. This chapter will try to shed some light onto this method, but without going deep into mathematical theories. We will rather stick to physical and engineering explanations to develop a better feeling for the use of a thermopile for temperature measurements. For those who are interested to go deeper, we recommend the literature, e.g. [4].

For this purpose, we will first motivate to think in terms of *heat flow* and not so much in terms of temperature when considering the use of a thermopile sensor in an application. If we see an object with a certain temperature one should immediately remember that it sends out a heat flow of a determined spectral characteristic and density. The amount of radiative power per wavelength, which is sent out per unit area into the surroundings is given by the curves in Figure 1. It now depends on the area and the view field of the sensor, how much will be absorbed. The absorbed heat then, will be led through the thermocouples and the membrane structure, finally reaching the silicon rim and the housing bottom as the heat sinks. The heat flow through the material results in a temperature gradient. Thus the two thermocouple ends – those located on the absorber and those on the silicon rim – will have different temperatures. For a constant heat flow this temperature difference is constant as well.

So far so good. It seems to be straightforward now to calculate the absorbed heat from the read voltage and the sensitivity figure, but it needs some more consideration to determine the temperature of the measured object.

The most important point and often forgotten, is, that the sensor itself emits radiation, which is a function of its own temperature. Therefore the net amount of radiation which is absorbed by the sensor is a function of the temperature *difference* between object and sensor. Thus, a thermopile –

and any other radiation sensor – generates a signal proportional to the temperature difference between sensor and object. This makes it necessary for a remote temperature measurement not only to record the temperature rise of the absorber, but also to register the temperature of the sensor itself. For this purpose, the PerkinElmer thermopiles include a thermistor in the sensor housing which changes its resistance with temperature. Sensors with ASIC have an electronic circuit integrated which generates a signal proportional to the absolute temperature (PTAT).

It can also happen, that the object temperature is lower than that of the detector itself. In this case there is a net radiation flow from the sensor to the object (of course heat always goes from hot to cold). The sensor's absorber decreases its temperature and the resulting signal voltage is negative.
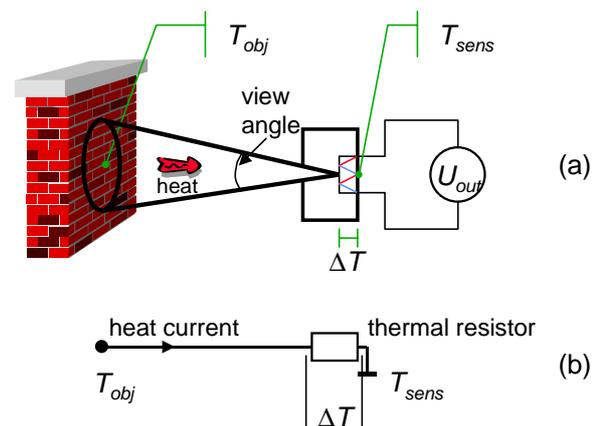
Figure 8: (a) The thermopile sensor as a current meter. It measures the heat current between the object and the thermopile housing by generating a small temperature drop, ΔT. (b) Equivalent electrical circuit. T_{obj} and T_{sens} are the two potentials which drive the heat current. This in turn generates the probing temperature ΔT.

We can therefore identify the thermopile sensor with a current meter that measures the heat current which flows between the object and the thermopile housing. Figure 8 illustrates the situation. The temperature difference between object and thermopile housing is the driving force (the voltage) for the thermal current. The thermopile resembles the (thermal) resistor that measures the current by building up a small temperature drop. This temperature drop in turn is converted into an electrical voltage.

This picture explains that a thermopile sensor is at first a heat flow sensor. Determination of the

object's temperature needs therefore the consideration of geometry, which means the field of view of the sensor and the area of the absorber. In practice, however, one employs a calibration procedure. This will be dealt with in the next paragraph.

4.1 Calibrating a thermopile for temperature measurements

There is the well known T^4-dependence of the total emitted radiation flux of a black body (Stefan-Boltzmann law). This dependence is also valid if dealing with temperature differences. Then the heat flux is proportional to $T_{ob}^4 - T_{sens}^4$, with index 'ob' denoting the object and 'sens' the sensor. (Remark: As sensor temperature one should correctly take the temperature of the absorber. But since the temperature drop over the sensor, i.e. from absorber to housing, is only in the mK-range, it is sufficient to identify the temperature shown by the internal thermistor with T_{sens}.)

In the simplest case, one can therefore use the following relation for the reading of a thermopile sensor:

$$U_{out} = K \cdot (\varepsilon T_{ob}^4 - T_{sens}^4).$$

The proportionality constant (sometimes called instrument factor) can simply be determined by sensing an object with known temperature. This procedure does not need any knowledge on sensor details such as absorber area and it is independent of the distance of the object as long as the sensor has a constant view angle (cf. Figure 8). In that case the distance between sensor and object has nearly no influence on the amount of exchanged heat and hence on the voltage reading, as long as the object fills the whole view field.

The emission coefficient, ε, is chosen to be 1 if the calibration is performed with a good black body. (For more details see paragraph 4.4)

The power factor value 4 is only correct, if (i) the whole wavelength spectrum is considered, (ii) the sensed object behaves as a good black (or gray) body, which means its radiation spectrum exhibits no exceptional peaks (color), and (iii) the sensor has a wavelength independent sensitivity.

The last point is mostly not fulfilled, since one usually senses in a certain wavelength range of the spectrum – for a thermopile, let's say between 5 and 20 µm. In this wavelength region most objects behave as black bodies.

This makes it necessary to modify the power factor to a smaller value – we will therefore write 4-δ.

This leads to the following ansatz for the calibration of a thermopile radiation sensor:

$$U_{out} = K \cdot (\varepsilon T_{ob}^{4-\delta} - T_{sens}^{4-\delta}).$$

Now there are two unknown parameters, K and δ, for which determination two equations and hence, two calibration temperatures are required. One needs therefore two objects at two different calibrated temperatures.

Since the two unknown parameters are not necessarily independent of both temperatures, T_{ob} and T_{sens}, this two-point calibration procedure is usually only sufficient, when limiting the object and sensor (ambient) temperature to restricted intervals. Allowing both intervals to vary within 50 K an accuracy of ±1 K is reachable. For 80 K intervals one should presume at least ±2 K. Only for very narrow temperature ranges, this method can deliver an accuracy as good as ±0.1 K.

4.2 Factors disturbing the accuracy

The above procedure is sufficient if the detector directly looks onto the measuring object and does not receive any other radiation. There are, however, components needed which define the optical path, the view angle and the spectral range. Therefore the sensor sees additionally the sensor cap which acts as an aperture and a filter or a lens, which are inserted into the optical path.

As long as these components have the same temperature as the sensor itself, no net radiation transfer takes place. In this case those objects are

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Thermal facts

If you want to measure the temperature of an object, you have to adjust the distance so that the thermopile *only* sees the object and nothing else. For this purpose a number of pyrometers have an additional internal light source (LED or laser spot) to mark the field of view. Thus, one can make sure, that the measurement spot does not overlap the region of interest.

Thermal facts

On the transparency of matter

Our daily experience tells us that glass is transparent. Therefore one might be astonished that the thermopile module delivers wrong results when sensing through a glass window.

One should remember that a green house is made of glass. This matter lets the sunshine in, which is absorbed by the plants and interior and thus converted to heat radiation. This infrared radiation is not able to escape, because for wavelengths above 2 μm, glass is completely impermeable.

On the other hand, there are substances, which at a first glance are intransparent. A slice of silicon, for example appears to be blue for our eyes, but it is virtually invisible for the IR measurement. Therefore silicon is the material of choice for infrared optical components.

Water is a substance, which often causes problems in infrared technology. Also, in this case, we might to be aware that water is indeed transparent to our eyes, but not for IR radiation. A very thin film of condensed water on the inlet window of a radiation meter can lead to completely wrong measurement results. The danger is that you might not be aware of the wrong reading – it is very much like the case, that your glasses are dirty: you still can see, but not as clearly as normal.

Thus take care to hold all infrared windows clean and free of moisture and ice.

invisible for the thermopile. Hence, a careful design of a radiation thermometer should assure that all optical components as apertures and filters have a good thermal contact to the sensor base plate (i.e. the thermal ground of the thermopile) and that there is additionally a weak thermal link of these components to the surrounding. The required weak link can be done by an additional shielding of the sensor.

Problems arise, if, let's say, the filter or the aperture are more affected by temperature changes from the surroundings than the sensor itself. This can happen if there is an extensive heat dissipation close to the sensor by e.g. switching on a

heater or the radiation thermometer is brought inside a warm room. Then, these components generate an additional signal. For applications, where this situation can be foreseen, it can be an advantage to attach an additional temperature sensor to the part in question (aperture, filter) and to record an optics temperature T_{optics}. It is then possible to extend the calibration equation from paragraph 4.1 as follows:

$$U_{out} = K \cdot (\varepsilon T_{ob}^n + K' T_{optics}^n - T_{sens}^n).$$

Now there appears the additional parameter K' in the equation, which determination makes a third calibration temperature necessary.

4.3 Practice of ambient temperature compensation

The output of a thermopile radiation detector is a function of the temperature *difference* of object and sensor. Therefore it is essential for the calculation of the object's temperature to know the temperature of the sensor, which in most cases is identical with the ambient temperature and to correct the measured value appropriately. This procedure is called *temperature compensation*.

For a computerized system, the procedure is more or less straightforward. From the thermopile signal one gets the value for the temperature difference. An additional device coupled to the sensor allows to determine the absolute temperature of the sensor. The two temperatures just have to be added.
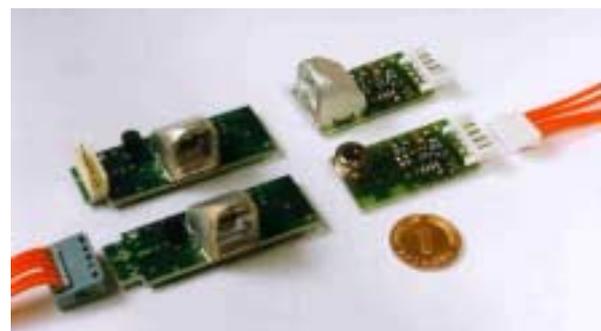
Figure 9: PerkinElmer Optoelectronics thermopile modules with mirror optics. The modules have an on-board signal amplification and temperature compensation and come completely calibrated – ready to plug-in. The employed system guarantees full interchangeability, which makes a manufacturing process easy. In case of service requirement, one can simply replace one module by another.

In its simplest form, the additional device for ambient temperature recording is a piece of a

semiconductor, which changes its electric conductivity with the temperature – this is a so-called thermistor. (There is one shown on the photo in Figure 5.) The thermistor's calibration curves are well specified. Measurement of conductivity is performed by sending a very low current through the thermistor and recording the voltage drop. The current must be kept low (lets say 1 μA) in order to avoid unnecessary heating.

PerkinElmer has developed thermopile modules (some of them are shown in Figure 9), where an analogue processor is employed for ambient temperature compensation. Here, a voltage signal is generated from the thermistor and added to the voltage from the thermopile in a second amplifier stage (cf. Figure 10). This additionally generated voltage must of course be equivalent to one that would be delivered by the thermopile, if working at a fixed reference temperature (0 K or 0 °C) and sensing an object at ambient temperature. Usually this is performed by adjusting the amplification of an operational amplifier as illustrated in Figure 10.
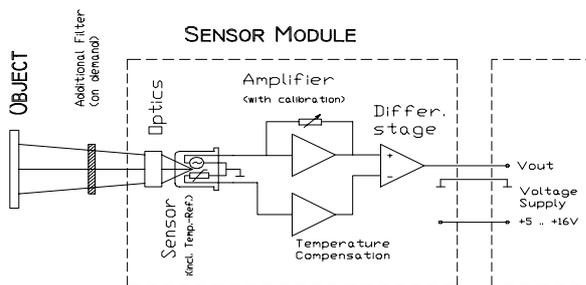
Figure 10: Thermopile sensor with analogue ambient temperature compensation. The output signal still shows the $T^{4-\delta}$-behavior, but now independent of the ambient temperature.

The output of the circuit in Figure 10 is a voltage that only depends on the object temperature as

$$U_{out} = K \cdot \varepsilon T_{ob}^{4-\delta},$$

with K now additionally including the overall amplification factor of the circuit. The calibration procedure can be performed as usual.

4.4   On the emission coefficient

In chapter 4.1 the emission coefficient, ε, was introduced. It is a measure of how efficiently a surface emits energy compared to a surface at the same temperature that is a perfect emitter. The emission coefficient can therefore take values between 0 and 1. Human skin is one of the highest emitters with $\varepsilon = 0.98$. Most other nonmetallic

surfaces such as paint, wood and plastic, also have high emissivity values – usually over 0.8. Because of their easy movable electrons, metals, especially shiny ones, do not emit radiation energy efficiently. Their emission coefficients are low, typically between 0.05 and 0.2.

Shiny metals are inefficient emitters. This means that shiny surfaces will seldom give us a reliable indication of their true temperature. Shiny metals are also highly reflective – they are thermal mirrors, which make you to measure the reflected surrounding instead the object itself. An aluminium steam pipe can be very hot when it may look cool by the thermopile measurement!

One might think it is sufficient to input a low emission coefficient into the measurement system and then the result will be accurate when sensing a piece of metal. But the signal received by the sensor is usually not only distorted because of its low intensity, but also by the reflections mirrored from the surroundings onto the absorber. Thus, without addressing background temperature, relative humidity and distance to target, an accurate measurement is impossible if the emission coefficient is lower than, lets say, 0.5.

➔ Whenever possible, change the surface emissivity to something higher. For instance, place tape or a paint spot on the metal.

5   Frequently asked questions

Why do I have to use a filter in front of the thermopile?

The thermopile sensor calculates the temperature from the intensity of the received radiation. The procedure is based on the theoretical black body (thermal) radiation behavior. If the radiation contains any enhanced components, which means the object has some "color", the calculation will be incorrect. In the infrared region for wavelengths above 5 μm most objects show the black body radiation curves (modified by the emission coefficient), thus allowing an accurate measurement. Even painted surfaces, which definitively have a color in the visible region, behave as a black body in the infrared. A filter in front of the thermopile therefore assures, that only the desired IR radiation hits the absorber.

The filter has an additional positive effect. It protects the thermopile structure from contamination by dirt or gases. Another window placed in front of the optics (essential in microwave or

Design hint

Smoothing out ambient temperature swings

Imagine that your infrared temperature measuring system is stored at a warm place, but you need it urgently to check some thermal conditions at a machine, which is working outside in the cold winter.

When bringing your thermopile device outside, the optics usually cools down much faster than the sensor itself. A measurement procedure, without waiting for thermal equilibrium of the whole device will then affect the temperature reading – in this case the meter will show a lowered value.

To speed up the time until thermal equilibrium is reached, one might think that it is of advantage to design the system in a way which assures a good thermal contact of the sensor to the ambient. Such an intense coupling, however, will lead to large noise signals, since small spatial inhomogeneities in the temperature of the surrounding are then easily to be seen in the output signal. Just imagine your warm hand moving in the vicinity of the sensor housing. It will immediately lead to small changes in sensor temperature and thus to output signal fluctuations.

Instead, one should go the opposite way: Give the sensor housing a large thermal mass, by e.g. encapsulating the sensor in a massive metal block.

...continued:

This system which now possesses a large heat capacity is to be further connected to the ambient by very weak thermal links — perhaps by employing thin plastic connections to an outer plastic housing representing a large thermal resistance.

It now corresponds to a thermal RC-circuit which acts as a thermal low pass and smoothes out ambient temperature fluctuations. This reduces drastically the mentioned thermal noise, assuring a very stable measurement.

If there is now an ambient temperature swing as in our example, the sensor system will reach the new thermal equilibrium state with a long, but now easy to determine time constant. The long transient time seems at first to be of disadvantage, but since the system's behavior is now well characterized, one can straightforwardly include a correction routine in the temperature calculation, which derives its correction value from the time derivation of the output signal. For small and very slow temperature changes, a correction may even be not necessary, since the developing temperature gradients in the sensor system are then negligible.

In conclusion: A large thermal RC-value will make the measurement less susceptible to temperature inhomogeneities in the surroundings and additionally to slow temperature changes of the ambient temperature as a whole. Very stable readings are received.

cooking applications) protects the sensitive and difficult to clean reflecting surfaces from condensed grease and vapor, especially water. The filter itself is easy to clean – and it is important to hold it clean (see the "thermal facts" box "on the transparency of matter").

Why do I have to correct my signal for the ambient temperature?

The amount of radiation received by the thermopile sensor is dependent on the temperature *difference* between object and sensor itself. Therefore the sensor temperature (this is mostly identical with the ambient temperature) must be recorded and considered. This is generally done by using a thermistor.

How do I use the internal thermistor in the thermopile?

The thermistor senses the temperature T by changing its resistance R as a known function of temperature. Please ask for the tabulated $R(T)$ values for the employed thermistor types. To measure the actual resistance during thermopile operation, one has to send a known electrical current through the device and measure the resulting voltage drop. Please keep in mind that the current through the resistor, however, dissipates heat in the thermopile housing which may change

the temperature of the sensor. To hold this heat source as small as possible, the measuring current must be kept to a minimum. A value of 1 to 5 µA is mostly sufficient for an accurate measurement.

What circumstances can adversely affect my sensor readout?

The most severe problems arise from temperature swings of the optics. If the sensor cap or the filter or lens change their temperature much faster than the sensor base plate, i.e. the sensor itself, then this will act as an additional signal source and influence the sensor output signal. If the heating is large, it can even happen that the amplifier goes into saturation. One way how to deal with this problem is explained in the above box "design hint".

What to do if I am interested to know more about thermopile implementation?

Please contact PerkinElmer Optoelectronics directly in Wiesbaden, Germany, or through one of the various offices worldwide. Their addresses together with additional information are obtainable from our websites:

http://www.perkinelmer.com or contact directly:

6   Literature

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