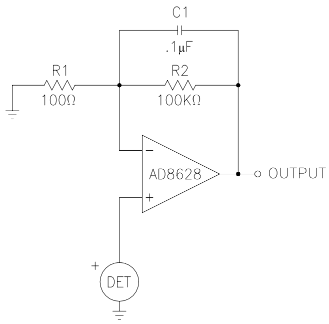
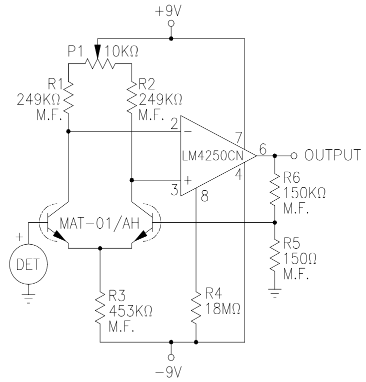
Example Amplifier Circuits

Common Amplifier



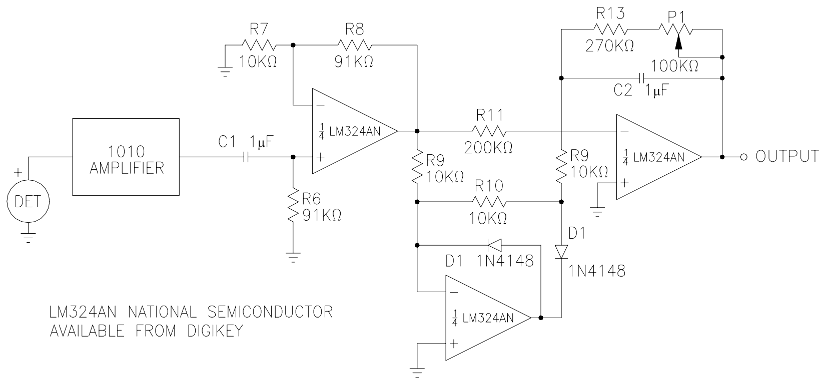
AMPLIFIER CIRCUIT WITH GAIN OF 1,000
BANDWIDTH (−3db) DC TO 15.9Hz

Micro Power Amplifier



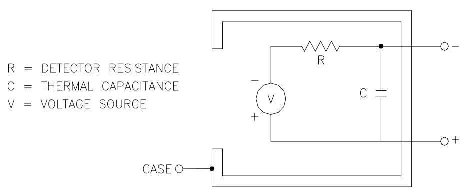
MAT−01/AH ANALOG DEVICES AVAILABLE FROM NEWARK ELECTRONICS
LM4250CN NATIONAL SEMICONDUCTOR AVAILABLE FROM DIGIKEY
M.F. = METAL FILM RESISTOR

Modulated Signal Rectifier For 10Hz (Full Wave)



LM324AN NATIONAL SEMICONDUCTOR
AVAILABLE FROM DIGIKEY

Equivalent Circuit for Thermopile Detector



For an Example of a Low offset, Low Drift amplifier data sheet, see Cirrus Logic CS3011

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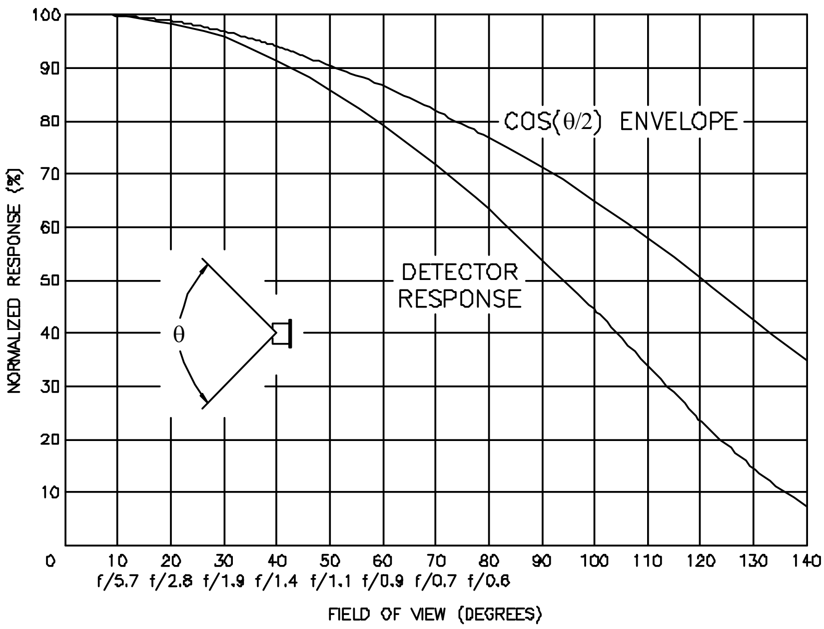
Detector Normalized Angular Response



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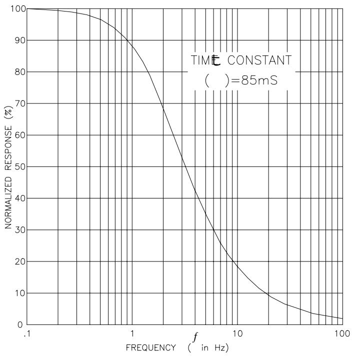
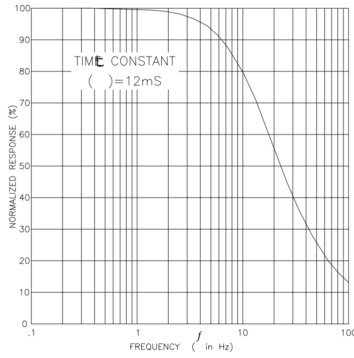
Detector Normalized Response as a Function of Frequency

$$\frac{R(f)}{R(o)} = (1+(2\pi f T)^2)^{-1/2}$$





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Blackbody Spectral Radiance

1. Blackbody radiance for three spectral regions*

$$L = \int_{\lambda_1}^{\lambda_2} \frac{C_1}{\pi\lambda^5} \bullet [e^{(C_2/\lambda T)} - 1]^{-1} d\lambda \quad W/cm^2 sr$$

L	-30	-20	-10	0	10	20	30	37	40	50	°C
8-13µm	1.58	1.98	2.44	2.96	3.55	4.21	4.93	5.49	5.73	6.60	$\frac{mW}{cm^2 sr}$
7-15.5µm	2.6	3.2	3.9	4.7	5.6	6.6	7.7	8.6	8.9	10.3	
1.8-25µm	5	6	7	8	9	11	13	14	15	17	

2. Differential blackbody radiance for three spectral regions*

$$\frac{\partial L}{\partial T} = \int_{\lambda_1}^{\lambda_2} \frac{C_1 C_2}{\pi\lambda^6 T^2} \bullet e^{(C_2/\lambda T)} \bullet [e^{(C_2/\lambda T)} - 1]^{-2} d\lambda \quad W/cm^2 sr\ ^oC$$

∂L/∂T	-30	-20	-10	0	10	20	30	37	40	50	°C
8-13µm	36.9	42.9	49.1	55.6	62.4	69.3	76.3	81.3	83.5	90.7	$\frac{\mu W}{cm^2 sr\ ^oC}$
7-15.5µm	57	66	75	85	95	106	117	124	128	139	
1.8-25µm	90	103	116	131	148	165	184	198	204	226	

*C_1 = 37,413 W$\mu m^4/cm^2$; C_2 = 14,388 µmK; T = 237 + °C

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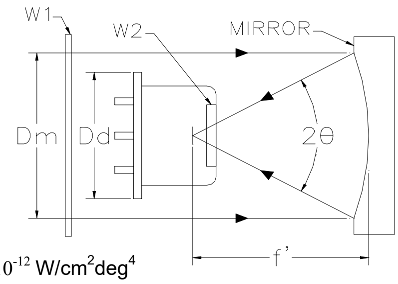
Detector Signal Calculation



Power On Detector: $\Delta\Phi = \tau_0\tau_1\tau_2\rho(\Delta L)\pi \mathrm{SIN}^2\theta\mathrm{Ad}$ Watts

$\theta \approx \mathrm{TAN}^{-1}\left(\frac{Dm}{2f'}\right)$; $\Delta L = \frac{4\sigma T^3 \Delta T}{\pi}$

Where:

$\tau_1\tau_2$ = Transmission of Windows W_1 & W_2

$\tau_0 = 1 - \left(\frac{Dd}{Dm}\right)^2$

ρ = Mirror Reflectance

$\sigma = 5.6686 \times 10^{-12}$ W/cm^{2}deg^4

T = 273 + °C (T in Kelvin)

Ad = Detector Area in cm^2

$\mathscr{R}$ = Responsivity

Voltage from Detector: $\Delta V = \mathscr{R}\Delta\Phi$ Volts

Signal to Noise Ratio: $(S/N) = \mathscr{R}\Delta\Phi/N$; Where N = Amplifier & Detector Noise

Sensitivity:

$$\Delta T = \frac{N(S/N)}{\tau_0\tau_1\tau_2\rho(4\sigma T^3)(\mathscr{R}\mathrm{Ad})\mathrm{SIN}^2\theta}\ {}^{\circ}\mathrm{C}$$

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Application Brief 1:   A Simple DC Radiometer

One of many applications of the thermopile detector is the remote measurement of temperature. In this Application brief we explain the basic principles of remote temperature measurement. Every object at temperature T (above absolute zero - 273.15°C) emits electro-magnetic radiation. The total amount of power or radiant flux (Φ) emitted per unit solid angle and per unit area over all wavelengths is given by the Stefan-Boltzman law [1]. Where the Stefan-Boltzman constant is given as:

$$\sigma = 5.6703 \cdot 10^{-12} \frac{W}{cm^2 K^4}$$

For a lambertian source the radiance (L) is:

$$L(\varepsilon, T) = \frac{\varepsilon}{\pi} \cdot \sigma \cdot T^4$$

Where ε is the emmisivity of the object surface. Thermopile detectors respond to thermal energy emitted by any object in it's field of view by producing a voltage that is proportional to incident power. This response is called the responsivity (R) of the detector. As an example, Dexter Research's model 1M has a typical responsivity of:

$$R = 23.2 \frac{V}{W}$$

The net power exchange between an object (source or target) and a thermopile is influenced by the following factors:

- temperature of the source T_s and detector T_d;
- area of detector and source, as well as the shape, orientation, and distance between them;
- additional objects in the path (for example: optics);
- the radiative characteristics of all surfaces, such as emissivity;
- medium between detector and an object (for example: atmosphere and moisture).

Lets consider the simple case of a circular source and circular detector parallel to each other with a common optical axis, where the source does not fill the detector's FOV [2]. As an example, we will use the following values:

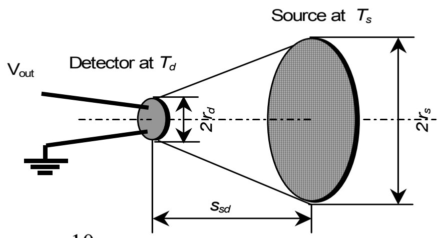
radius of the source: $r_s = \frac{10.6}{2} cm$

radius of detector: $r_d = \frac{1.0}{2} mm$

emissivity of source: $\varepsilon_s = 1.0$

emissivity of detector $s_{sd} = 10cm$

distance between the source and detector: $s_{sd} = 10cm$



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The dimensions of the system in our example, are partly included in a "real body view factor", or *transfer factor* F_{sd} . Siegel and Howell [3] provide the calculations and a large catalog of transfer factors for different geometries. F_{sd} for the example above, can be calculated using the following expression [1,3]:

$$F_{sd} = \frac{2\pi \cdot r_d^2}{r_s^2 + r_d^2 + s_{sd}^2 + \sqrt{\left(r_s^2 + r_d^2 + s_{sd}^2\right)^2 - 4 \cdot r_s^2 r_d^2}}$$

F_{sd} for the example above, can be calculated using the following expression [1,3]:

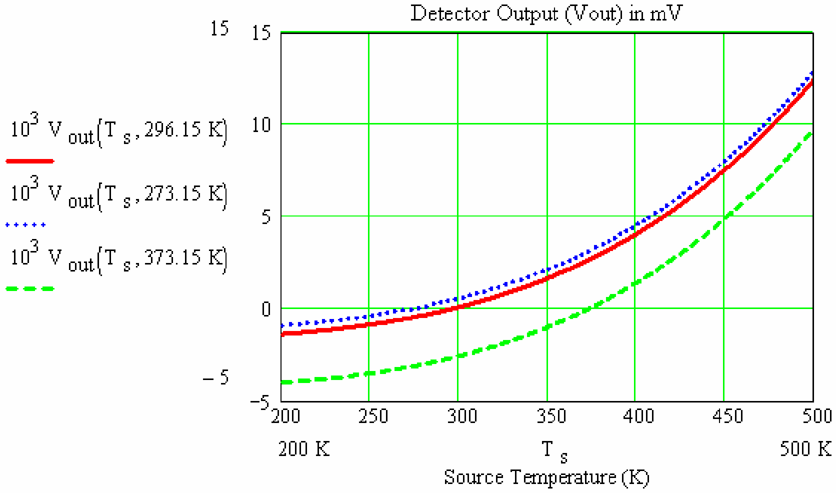
The net power exchange through radiation can be defined as in [4]:

$$\Phi\left(T_s, T_d\right) = \frac{\sigma \cdot \varepsilon_s \cdot \varepsilon_d \cdot A_s \cdot F_{sd}}{\pi} \cdot \left(T_s^4 - T_d^4\right)$$

Where A_s and A_d are the areas of source and detector respectively. For the case where the active area of the detector is square, use a circular detector of equal area. This will yield a close numerical solution. Knowing the responsivity of a detector and the net power exchange from the source, the output signal V_{out} can be estimated as:

$$V_{out}\left(T_s, T_d\right) = R \cdot \Phi\left(T_s, T_d\right) \qquad V_{out}(500K, 296.15K) = 12.418\,mV$$

In the figure below V_{out} is presented as a function of T_s for three detector temperatures:



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Above, we have shown an example of a simplified system. In reality the solution to the radiant power exchange problem is quite complex. However, to calibrate an actual instrument the following empirical formula can be used:

$$V_{out} = F \cdot \left(\varepsilon \cdot T_s^{\,n} + F1 \cdot T_{opt}^{\,n} - T_d^{\,n} \right)$$

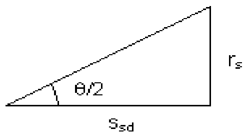
Where F and F1 are constants that depend on geometry, T_{opt} is the temperature of the optical components of the radiometer, and the power factor n is different from 4 due to the limited spectral range of a particular radiometer. Temperatures T_{opt} and T_d can be monitored by temperature sensors, for example LM20 from National Semiconductors. The other 3 constants: F, F1, and n can be determined by a 3 point calibration for each individual instrument.

<u>References</u>:

1. E.F. Zalewski, "Radiometry and Photometry," in M. Bass, editor in chief. Handbook of Optics, vol. II, 2nd ed., Optical Society of America, 1995, pp. 24.17, 24.26.

2. When the source fills the entire detector's FOV, please use the following equation to calculate r_s :

$$r_s = s_{sd} \cdot \tan\left(\frac{\theta}{2}\right)$$, where θ = Detector FOV



3. R. Siegel and J.R. Howell. "Thermal Radiative Heat Transfer", Hemisphere Publishing Corp., Washington, D.C., 3rd ed., 1992.

4. J.H Lienhard IV and J.H. Lienhard V, "A Heat Transfer Textbook", Phlogiston Press, Cambridge, Massachusetts, 2001, p. 531.

<u>Note</u>: *This application brief can be* ***downloaded*** *as a* ***Mathcad document*** *at www.DexterResearch.com (see the "Technical Briefs" tab, then click* ***"Download Mathcad Version"****. You can then enter your own parameters into the boxed equations above and Mathcad will calculate the results. This download will require Mathcad 2001 or newer.*

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Temperature Compensation of DC Radiometer

Engineering note: This Application Brief uses old technology and is therefore provided as a starting point only. We plan to revise this brief in the future.

The thin film thermopile detector like its forefather, the wire thermocouple, requires either a reference junction temperature measurement or a constant temperature sink for its reference junction. The later is usually difficult to implement in an instrument because of size and weight requirements. The detector reference junction temperature can be measured by attaching a temperature transducer to the detector case. Some of the transducers that have been used are:

1. Thermistor bead, e.g. Yellow Springs Instruments, YSI-44201
2. Signal diode, e.g. 1N4148
3. Integrated circuit, e.g. Analog Devices AD590

One characteristic common to these devices is that they require power to operate, and therefore, result in self heating. The instrument designer must exercise extreme caution not to upset the delicate thermal balance between the thermopile detector's active and reference junctions by introducing thermal transients from the temperature transducer's self heating. Keeping this caution in mind, we will proceed to design a temperature compensated DC radiometer.

There are three main tasks in implementing a temperature compensating network. These tasks are:

1. Attach the temperature transducer to sense the thermopile's reference junction.
2. Design a circuit to combine the detector voltage with the compensating voltage.
3. Scale the voltages to a fixed calibration scheme.

The predominate mode of heat transfer to and from the thermopile's reference junctions is through the TO-5 header leads and the header itself. These leads (with internal heatsink models and ST model detector) are thermally isolated from the TO-5 case by a glass to metal bond, which seals the leads to the header. Since our job is to measure reference junction temperature, between these leads is the ideal site to attach our temperature transducer. This transducer should be outside the TO-5 case. A short experiment will explain why. In typical radiometer applications, there are a few µW incident on the detector's active junctions from the object to be measured. However, the temperature transducer has an internal self dissipation of several hundred µW. These µW's are received more efficiently by the detector because of the large solid angle ~3sr. In comparison, an f/1 optical system will have a solid angle of ~0.63sr, which is nearly a

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factor of 5 less. The point is that device self heating causes a signal hundreds of times greater than the signal we are trying to detect. The proper attachment of a temperature transducer is shown in Fig. 1. The salient features are:

1. The device is thermally well coupled to the detector leads, and by lead conduction to the detector reference junctions.
2. The device is thermally coupled to the detector header, thereby damping thermal transients.
3. Device self heating is conducted away by the detector holder (not shown in Fig. 1).

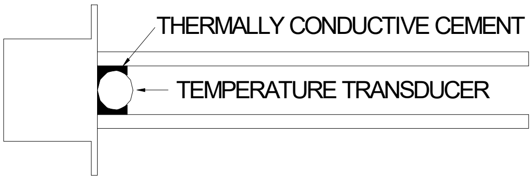

Fig. 1. Temperature Transducer Attached to Detector Leads.

The circuit design will be based on the YSI-44201 Thermistor. The basic principles are identical for the other devices, only the circuit details would be altered. Fig. 2 shows a circuit using a Thermistor bead B1 attached to a detector model 1M. A1 amplifies the detector voltage and R3 is used to calibrate the instrument. The voltage V_1 has the form

$$V_1 = k(T_t^4 - T_d^4) \qquad (1)$$

Where k = systems constant which includes Detector Parameters (see equation for V_{det} on page 2 of Application Brief 1), optical system, and the gain of A1

T_t = absolute target temperature in Kelvin.
T_d = absolute target temperature in Kelvin.

If the inputs to R7 and R8 are zero, then the output of A3 is

$$V_0 = -\frac{R9}{R3} K[T_t^4 - T_d^4] \quad \text{or} \quad V_0 = -\frac{R9}{R3} kT_t^4 + \frac{R9}{R3} KT_d^4 \qquad (2)$$

From this result we see that a voltage equal to $\frac{R9}{R3} kT_d^4$ must be subtracted from V_o to compensate for the detector reference junction temperature.

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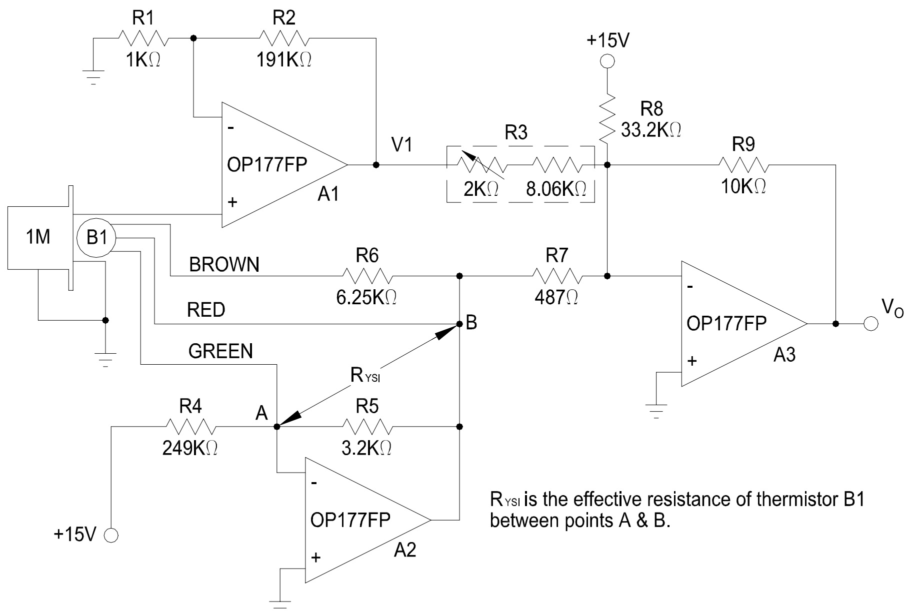

Fig. 2. Radiometer Circuit with Temperature Compensation.

The voltage from A2 is

$$V_T = -15\,\frac{R_{YSI}}{R4} \qquad \text{or} \qquad V_T = -\frac{15V}{R4}\,(2768.23 - 17.115T_c) \qquad (3)$$

Where R_{YSI} = 2768.23 - 17.115T_c, T_c = detector case temperature in °C, and the decimal numerical values are taken from the YSI-44201 data sheet with values for R5 & R6 as shown. This voltage, along with the detector voltage and reference voltage at the top of R8, are summed by A3. The final output voltage of A3 is

$$V_0 = -\frac{R9}{R3}\,kT_t^4 + \left[\frac{R9}{R3}\,kT_d^4 - \frac{R9 \cdot 15}{R7 \cdot R4}\,(-2768.23 + 17.115\,T_c) - \frac{R9 \cdot 15}{R8}\right] \qquad (4)$$

When the bracketed term is zero the radiometer is compensated and the voltage from A3 is

$$V_{0\,(compensated)} = -\frac{R9}{R3}\,kT_t^4 \qquad (5)$$

This result will be the basis of our calibration scheme.

In application brief 1, a simple radiometer was shown that had a temperature range from 0°C to 200°C. The result of that design is repeated here in Table 1.

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Target Temperature (T_t)		Detector Voltage (V_{det})	Compensated Voltage (V_0)
K	°C	mV	mV
273	0	-1.62	5.18
298	25	0.46	7.35
323	50	3.14	10.01
373	100	10.71	18.04
473	200	38.14	46.64

Table 1. Un-amplified Detector Voltage for a Simple Radiometer w/ ambient temperature = 20°C.

For this design we will let a target temperature of 200°C give 10 volts at the output of A3. The gain of A1 can be calculated as G = 10/.04664 = 214.41. Since detector responsivity will vary from detector to detector by ±10%, we will approximate G with the gain of A1 and set, using available resistor values to approximate G, R1 = 1K and R2= 191K. Giving the gain of A1 as 192. The ratio of R9/R3 will be adjusted during instrument calibration to give the desired system gain to give an output of 10V a 200°C.

The next step is to determine the instrument constant, from equation 5 when V_0=10V at T_t=473K

$$\frac{R9}{R3} k = -\frac{10}{(473)^4} = -1.998 \times 10^{-10} V/K^4 \qquad (6)$$

We will assume that the radiometer will be used in ambients from 0°C to 50°C. Using the previously determined instruments constant and ambient temperature range we can plot the required compensating voltage (fig. 3) in order to give an accurate output voltage proportional to the target temperature.

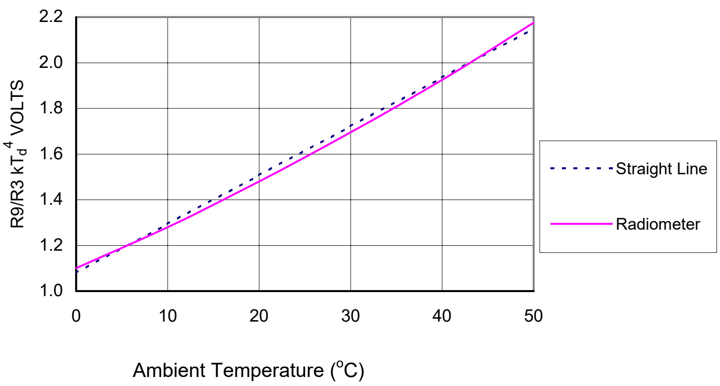

Fig. 3. Required Compensating Voltage $\frac{R9}{R3} kT_d^4$ from equation 4 verses ambient temperature with a Straight Line Fit.

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The dashed line shows the linear voltage fit from the Thermistor (1.08V@0°C and 2.15V@50°C). For an equation of the form $V_c = mT_c + b$ we have

$$b = 1.08;\ m = (2.15 - 1.08)/50$$

or

$$V_c = .0214T_c + 1.08 \qquad (7)$$

Equating like coefficients of the bracketed part of equation 4 and equation 7

$$\frac{-R9 \cdot 15}{R7 \cdot R4} 17.115T_c = -0.0214T_c \qquad (8)$$

To keep Thermistor self heating low let R4 = 249KΩ. Using equation 8 and solving using standard resistor values, let R9 = 10KΩ which gives R7 = 482Ω. Selecting the closest 1% resistor we let R7 = 487Ω.

$$\frac{R9 \cdot 15}{R7 \cdot R4} 2768.23 - 15\frac{R9}{R8} = -1.08 \qquad (9)$$

Solving equation 9 for R8 we have R8 = 33.3KΩ. Again selecting the closest 1% resistor R8 = 33.2KΩ.

Summarizing: R9 = 10KΩ, R8 = 33.2KΩ, R7 = 487Ω and R4 = 249KΩ. Substituting these values into the bracketed terms of equation 4 and using equation 6 we have

$$\Delta = -\,1.998 \times 10^{-10}T_d^{\,4} - 1.09376 - .02117T_c \qquad (10)$$

Fig. 4 shows a plot of voltage error of equation 10.

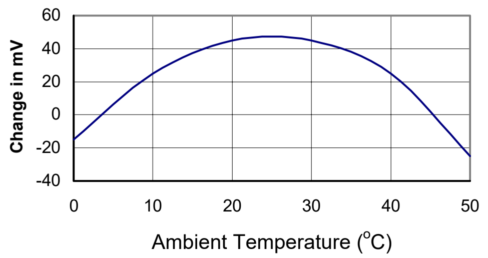

Fig. 4. Error in Compensating Voltage caused by Linear Fit of 4th Power law.

This application brief has shown in detail, one method of temperature compensating a DC thermopile radiometer. Simple circuitry and 1% resistors were used along with a bead thermistor. The basic principle described may be implemented using other temperature transducers.

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