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Fyss300/3 Temperature sensors

Supervisor:

Abstract

This research studied the behaviour of four different thermometers: thermocouple, resistance thermometer Pt100, thermistor and PN diode. During the measurements the thermometers were heated in a cup full of water from 8°C to 96°C. About at 10°C interval we collected the measurement information for thermocouple voltage, Pt100 resistance, thermistor resistance and PN diode voltage. Using those values I made plottings using gnuplot. To figure out sensitivities of the studied thermometers I made the linear fittings for thermocouple, Pt100 and PN diode and a simple expotential fittings to thermistor. The linear fittings were obviously suitable for measured values, but expotential fitting didn't follow the measured values so well. Additionally I made a fitting for thermistor with Steinhart-Hart equation and found out Steinhart-Hart equation gives the better fitting than an expotential function.

Contents

1 Introduction

In this research we studied resistance thermometer, thermistor, semiconduncting diode and thermocouple. Any of them operates differently due to dissimilar structure.

Thermocouples operation is based on Seebeck effect,[2, p. 87] which has invented by Estonian physicist Thomas Seebeck in year 1821. Seebeck effect means when two metals of junctions are at different temperature, there occurs a potential difference.

Both the resistance thermometer and the thermistor are based on resistance measuring. In the resistance thermometer is a conductor, whom resistance changes when temperature changes. Thermistor include semiconducting materials, whom resistance also changes when temperature varying. Thermistor is smaller and more sensitive than Pt100.[2, p. 92]

The fourth studied sensor was semiconductor junction thermometer, which is forward biased PN-diode. Diode's operation as thermometer is based on the voltage change.

2 Theoretical background

2.1 Thermocouples

Using thermocouple as a thermometer it's needed to measure voltage difference between the two metals of junction. The difference of potential is proportional to temperature, which makes it possible to define temperature by measuring voltage.

Thermocouple has two sensors. One of them must be kept in reference temperature, which should be about 0°C. And another sensor is supposed to keep in the studied temperature.

The Sensivity of thermocouples S can be calculated as a relation of voltage and temperature

$$S = \frac{dU}{dT}, \tag{1}$$

where U is voltage and T temperature.

2.2 Resistance thermometer

Let's see the resistance thermometer case. In this experiment we used a type Pt100 resistance themometer made of platinum. The name Pt100 comes from the fact that resistance at temperature 0° is 100Ω.[2, p. 91]

When the temperature regions is small enough the resistance R of Pt100 sensor can be defined by a linear equation

$$R(t) = R(t_0)(1 + \alpha(t - t_0)), \tag{2}$$

where t is a temperature, t_0 is 0° and α is a constant.

2.3 Thermistor

For termistor the resistance is between tens Ω and megas Ω. As we can see in the Steinhart-Hart equation below, the resistance R is highly non-linearly dependent on temperature T:

$$\frac{1}{T} = a + b \log R + c \log^3 R. \tag{3}$$

The terms a, b and c are constant.

2.4 Semiconductor junction thermometer

Semiconductor junction thermometer is a diode, which makes it possible to use Shockley equation

$$I_D = I_S(T)(e^{\frac{eV_D}{nkT}} - 1), \tag{4}$$

where I_D is a current over the diode, I_S the current made by bias, k Boltzmann's constant and n is a constant, which can be 1 or 2. Typical values for $I_S = 6,3n\text{A}$ and $n = 2$.

3 Experimental methods

Before measurements the supervisor set up the couplings of electronic components. The most complex setting was the diode, which needed a connecting plate. The connecting plate (Bimboard 3) was coupled with resistor, DC Power supply EP-603 and IN4148 diode. The coupling was accordant with the figure 1. The voltage V_D was measured with Finest 203 and current I_D with Finest 703.

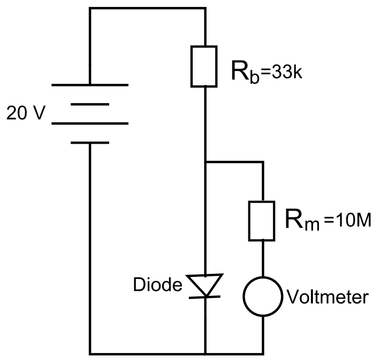


Figure 1: Connecting plate with diode

Then the other thermometers were set up. Thermopair's reference sensor was put to the small cold cup with some ice and we tried to keep it at constant temperature. The temperature in small cup was measured with Hg meter and it held between 2° and 3°. The another head of thermopair was putted to the bigger cup and we measured the voltage between sensors with Digital Voltage meter GW (model-gdm-8055).

Both thermistor and resistance thermometer consist of only one sensor and they were putted to the bigger cup. In case of resistance thermometer the resistance was measured with Kenwood DL-2051 and the thermistor's resistance was measured with Finest 203 voltage meter.

The experiment was performed with the setup in the figure 2, in which we can see all the thermometers' sensor is putted in the same big cup. The water in the cup was heated by a "cooker", or hot plate IKAMAG RH. In both of the cups were placed mercury thermometers, which we watched.

We measured probes of all the thermometers at the same time starting about a temperature 8° and took several values until the temperature has rised about 96°. During the measurements we collected the numerical values of voltages, current and resistances for the temperature values in Hg thermometers at about 10-degree intervals.

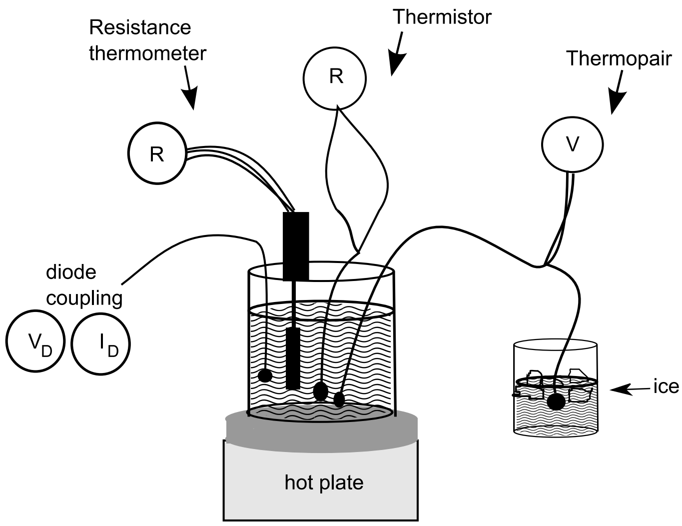


Figure 2: Experiment setup

4 Results

The measuring results for Hg meters and every studied thermometers are listed in the table 1, where T is temperature given by Hg meter in bigger cup (see picture 2), T_0 temperature of the smaller cup, R_{th} thermistor resistance, R_{pt} platinum thermometer resistance, V_{pair} thermocouple voltage, I_D diode current and V_D diode voltage.

I made all the plottings and fittings with gnuplot 4.4 software. Codes for gnuplot I used in this study are in the attachment 2.

The accuracies for voltmeters and resistance meters are listed in the listing below. Accuracy values I checked from Internet exept the accuracy for resistance of Finest 203. I estimated the resistance accuracy of Finest 203 to be quite high to avoid defining total error to be too small.

- Kenwood DL-2051: 0.1% + 1 digit (Pt100 resistance)
- Finest 203: 5% (THermistor resistance)
- Finest 203: 0.5% + 2digits (diode voltage)
- GW Model-gdm-8055: 0.12% + 2 digits [1] (thermocouple voltage)
- Hg meter: 0.5K

T (°C)	T_0 (°C)	R_{th} (Ω)	R_{pt} (Ω)	V_{pair} (mV)	I_D (mA)	V_D (V)
8	2	4.34	103.027	0.178	0.58	0.595
10	2	4.37	104.327	0.325	0.58	0.588
20	3	3.98	108.271	0.724	0.58	0.567
30	3	3.62	112.343	1.110	0.59	0.546
40	3	3.25	116.244	1.514	0.58	0.523
50	3	3.03	120.450	1.977	0.58	0.503
60	2	2.95	124.150	2.462	0.58	0.482
70	2	2.799	127.900	2.835	0.59	0.461
80	2	2.743	131.740	3.316	0.59	0.436
90	3	2.723	135.970	3.757	0.59	0.411
96	2	2.751	137.440	4.015	0.59	0.401

Table 1: Measuring results

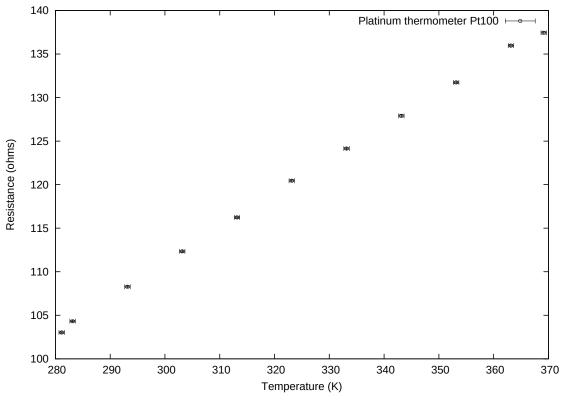
4.1 Plottings

Using the values of the table 1 I made plottings in figure 3 for every studied thermometer. In those plottings I transformed the temperature T from celsius degrees to kelvins by summing each of the T value with 273.15.

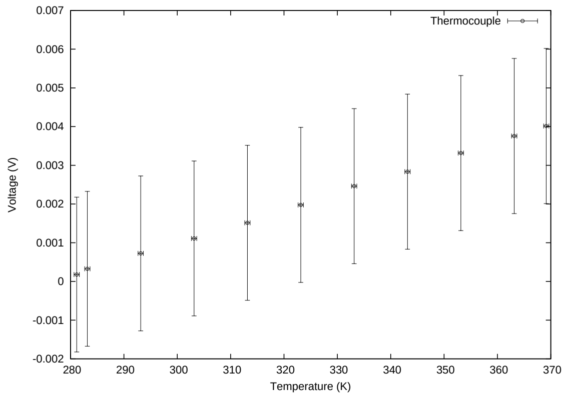
The picture 3(a) represents the platinum thermometer resistance dependence on the temperature. From this picture we can notice that resistance dependes on the temperature linearly. In the case of thermistor resistance the dependence is not linear, as we can see in the picture 3(c). The thermisor resistance differential coefficient seem to be negative, but it approaches the zero when temperature rising.

The voltage between the thermocouple junction is represented in the picture 3(b). There we can see the voltage dependes on the temperature linearly and it increases when temperature rises. The diode voltage in picture 3(d) also seems to be linear, but it decreases when temperature rising.

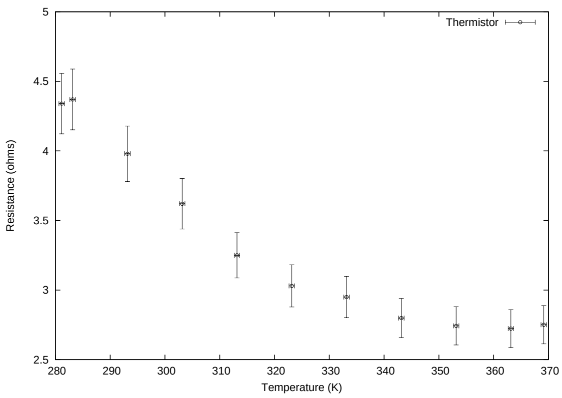
Also errorbars are shown in those plottings. The horizontal error means Hg meter error for temperature, which is only 0.5K for every measurepoints. It's quite small compared with the temperature scale in the plottings thus one can hardly even see those errorbars. The vertical errorbar is the error for measured value of thermometers. Because it dependends on the measured value as shown in listing below, it's different in every measurepoints.



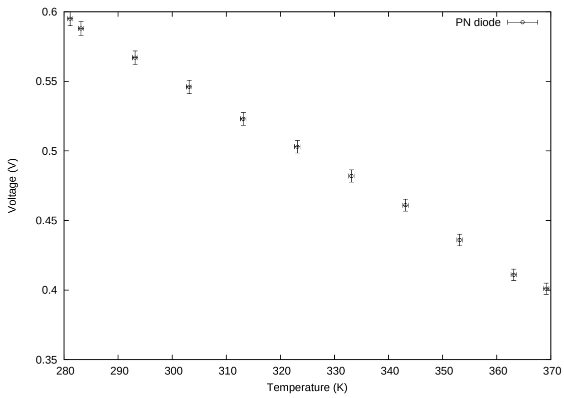
(a) Platinum thermometer resistance $R_{pt}(T)$



(b) Thermocouple voltage $V_{pair}(T)$



(c) Thermistor resistance $R_{th}(T)$



(d) Diode voltage $V_D(T)$

Figure 3: The plottings and errorbars for platinum thermometer, thermocouple, thermistor and diode at every measured temperature

4.2 Sensitivities

I obtained the sensitivities by making the fitting functions for plottings with gnuplot. The sensitivity value is the derivative of fitted function. Fitting functions and the constants given by gnuplot are listed in the table 2 and the obtained sensitivities are listed in the table 3.

I made linear fittings for platinum thermometer, thermocouple, thermistor and diode plottings, see the figures 4(a), 4(b) and 4(d). The fittings function in those case were of the form

$$f(x) = a + b * x, \tag{5}$$

where variable x means temperature and the variables a and b you can see in the table 2. In this case the sensitivity is b. The sensitivities of thermocouple and diode are easy to compare, because theirs units are the same (volt per kelvin) as like in equation 1. So we can notice the diode ($b \approx -0.002$) is much more sensitive than thermocouple ($b \approx 0.00004$).

The thermistor was clearly not linear as shown in picture 4(c), thus instead of linear fitting I used an expotential equation

$$f(x) = a * e^{\frac{b}{x}}. \tag{6}$$

Let's calculate the sensitivity by differentiating the equation 6

$$\frac{d}{dx} f(x) = \frac{d}{dx} a * e^{\frac{b}{x}} = \frac{-a * b}{x^2} e^{\frac{b}{x}}. \tag{7}$$

As the equation below shows, the sensitivity isn't constant, but dependent on temperature T. Because it's not possible to define a contant value for sensitivity of thermistor, I have calculated the sensitivity values in the lowest and highest measured temperature. Let's next calculate the sensitivity of thermistor in the lowest measured temperature $T_{min} = 8°\text{C} = 281.15\text{K}$ using the constants a and b shown in table 2

$$f(281.15\text{K}) = \frac{-0.46 * 630}{281.15^2} e^{\frac{630}{281.15}} \frac{\Omega}{\text{K}} \approx -0.034466 \frac{\Omega}{\text{K}}. \tag{8}$$

Then we calculate the sensitivity in the highest measured temperature $T_{max} = 96°\text{C} = 369.15\text{K}$

$$\frac{-0.46 * 630}{369.15^2} e^{\frac{630}{369.15}} \frac{\Omega}{\text{K}} \approx -0.011718 \frac{\Omega}{\text{K}}. \tag{9}$$

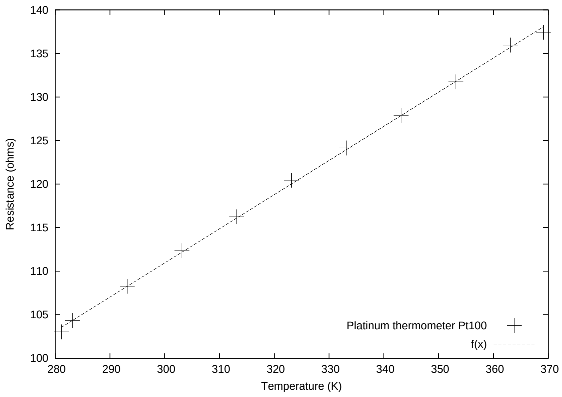
Thus between the temperature 8°C and 96°C the sensitivity is between $-0.034\frac{\Omega}{\text{K}}$ and $-0.012\frac{\Omega}{\text{K}}$, which is smaller than tenth of the sensitivity of thermistor $0.392\frac{\Omega}{\text{K}}$.

device	fitting	a	b
thermocouple	$a + b * x$	0.01200V	$0.0000433\frac{\text{V}}{\text{K}}$
diode	$a + b * x$	1.21V	$-0.00219\frac{\text{V}}{\text{K}}$
Pt100	$a + b * x$	6.7Ω	$0.392\frac{\Omega}{\text{K}}$
thermistor	$a * e^{\frac{b}{x}}$	0.46Ω	630K

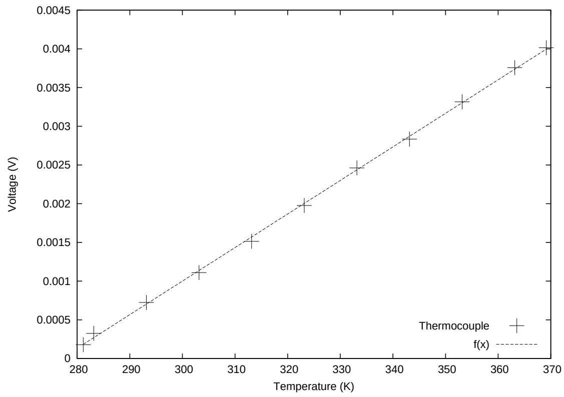
Table 2: Fitting functions for thermocouple, diode, Pt100 and thermistor

device	sensitivity
thermocouple	0.0000433V/K
diode	−0.00219V/K
Pt100	0.392Ω/K
thermistor	−0.034Ω/K ... −0.012Ω/K

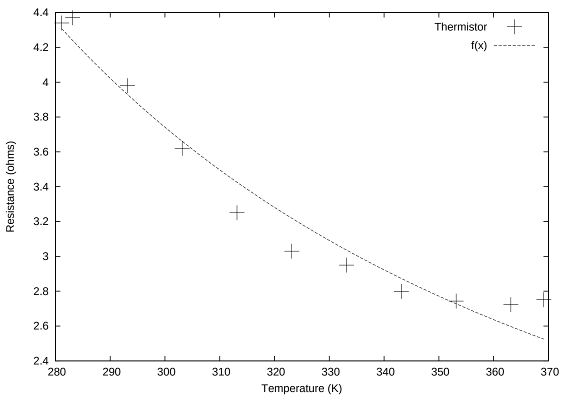
Table 3: Sensitivities of the thermometers measured between temperature 8°C and 96°C.



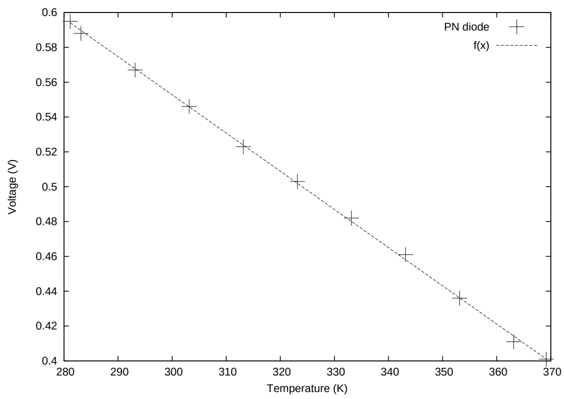
(a) Platinum thermometer resistance



(b) Thermocouple voltage



(c) Thermistor resistance



(d) Diode voltage

Figure 4: Fittings to the plottings

4.3 Steinhart-Hart equation

One can use Steinhart-Hart equation 3 for thermistor. I runned a fitting function of the form $\frac{1}{T} = a + b * log(x) + b * (log(x))^3$ with gnuplot. The code for this fitting is in the last section of attachment 2. The variable x is actually resistanse of the thermometer R.

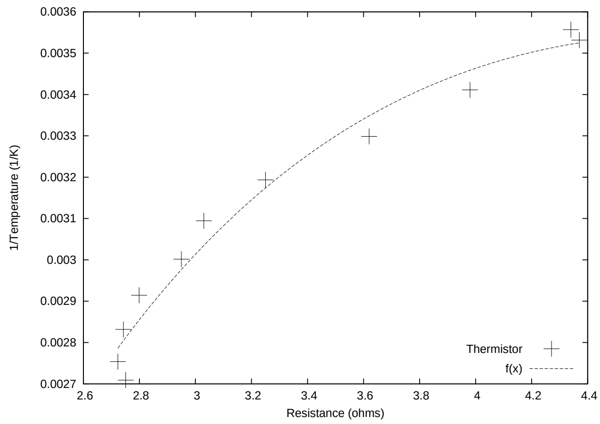


Figure 5: Steinhart-Hart equation fitting for thermistor

5 Conclusions

The thermocouple need the reference temperature, which may limit its usage. Additionally its sensitivity is low, thus it may be suitable when measuring high temperatures. On the contrary the diode has high sensitivity, it can be used when measuring small changes of temperature.

The same kind of conlcusion can be done with resistance thermometer and thermistor. Resistance thermometer sensitivity is lower than thermistors, thus it's more suitable for measuring big change of temperature. And Thermistor is suitable for measuring temperature in stabile system, when it's needed to observe only small changes of temperature.

As shown in section 4.2, the sensitivity of thermocouple was about $(0.0000433 \pm 0.0000004)\frac{\mathrm{V}}{\mathrm{K}}$. According to literature the sensitivity of K type thermocouple is $0.000042\frac{\mathrm{V}}{\mathrm{K}}$ [2, p. 88], which is a little smaller than the value in this research. Anyway one can conclude the studied thermocouple was K type.

I used two kind of fittings for thermistor in this report. Comparing the fittings with Steinhart-Hart equation in figure 5 and the expotential fitting in figure 4(c) we can notice the Steinhart-Hart equation conforms the experimental values better. Thus Steinhart-Hart is more suitable to represent the relation of resistance and temperature of thermistor than the simpler expotential function.

6 Attachments

Attachment 1: Measurement log
Attachment 2: gnuplot codes

References

[1] Instek gdm-8055 multimeter. `http://www.tequipment.net/InstekGDM8055.html`.

[2] O. Aumala. *Mittaustekniikan perusteet*. Otatieto, 7. edition, 2001. ISBN 951-672-306-3.