Versuch 41 **September 14, 2021**

Temperature measurement

Physics Begginer's Practical Course I

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Contents

1 Goal of the experiment

In this experiment, we aim to learn the basic principles of four different types of thermometers, the gas thermometer, the pyrometer, the resistance thermometer and the thermocouple. We will learn a little bit of how they work, but especially we want to learn how to operate them. As a test, we will gradually boil water and take different measurements at around every 10 degrees celsius, additionally, we will use mixtures of dry ice and alcohol and liquid nitrogen to take measurements at very low temperatures. Lastly, we will use the thermocouple to measure the temperature of a flame under strong and weak air supply.

2 Basics

2.1 Gas thermometer

A gas thermometer works according to the ideal gas law. This law assumes, that a gas is made up of point particles that don't interact with each other, i.e., they have only 3 degrees of freedom, in the 3 directions of space. According to this law, we can establisch a relationship between pressure p, volume V and temperature T in the following way:

$$p \cdot V = N \cdot k_B \cdot T \tag{1}$$

N describes here the number of particles and k_B is the Boltzmann constant. According to this law, if we keep the Volume constant, for example by enclosing a gas in a glas container, we can determine the Temperature by means of the pressure, which we can measure with a manometer. This system is flawed in two ways, however. For starters, we part from the assumption that we have an ideal gas, which is sadly, ideal. We can however simulate ideal conditions with certain gases and this is good enough for our experiment. Secondly, the changes in temperature slightly change the volume of the glass balloon. This effect is negligible.

2.2 Seebeck effect and thermocouple

A temperature difference or a temperature gradient between two dissimilar electrical conductors can produce an electric voltage. This occurs because valence electrons in one of the conductors are more energetic and therefore moving more rapidly towards the colder part. This effect produces a very small voltage, it can range up to the order of magnitude of milivolts. This voltage is proportional to the difference in temperature between both conductors:

$$U_{th} = K\Delta T \tag{2}$$

The constant K depends on the metals used for the conductors. Thermocouples aren't a good instrument to measure temperature, unless you can determine the temperature of one of the conductors as reference. Usually, room temperature can be assumed as reference temperature.

2.3 Platinum resistance thermometer

A resistance thermometer is a device, whose resistance on temperature depends. If this relationship is known, it is possible to convert this value to a temperature. In the case of the Platinum resistance thermometer, we can determine the resistance with the following polynomial

$$R(T) = R_0\Big(1 + AT + BT^2\Big) \tag{3}$$

and from that we can solve for the temperature:

$$T(R) = \frac{-R_0A + \sqrt{R_0^2A^2 - 4R_0B(R_0 - R)}}{2R_0B} \tag{4}$$

According to Ohm's Law, we could measure the resistance by either applying a constant voltage or a constant current and measuring the change in the other one. We will use the latter because the thermometer self-heats during the measure, so it is better to have a small current flowing, than a voltage. Besides this, we run into the problem that the internal resistance of the wires also plays a significant role if we just use a straight forward two wire circuit. We avoid this issue by connecting the devices in the following four wire circuit: The Voltmeter has a very high impedance, which prevents a lot of current from flowing through the wires.

2.4 Pyrometer

Bodies with temperatures higher than absolute zero emit a certain thermal radiation. This is based on the priniple of black body radiation, according to which bodies in thermal equilibrium emit thermal electromagnetic radiation. It parts from the assumption, that the object is opaque and can absorb all wavelengths, hence a literal *black body.* This radiation is mostly infrared, and at high enough temperatures, it begins to glow in a spectrum between red

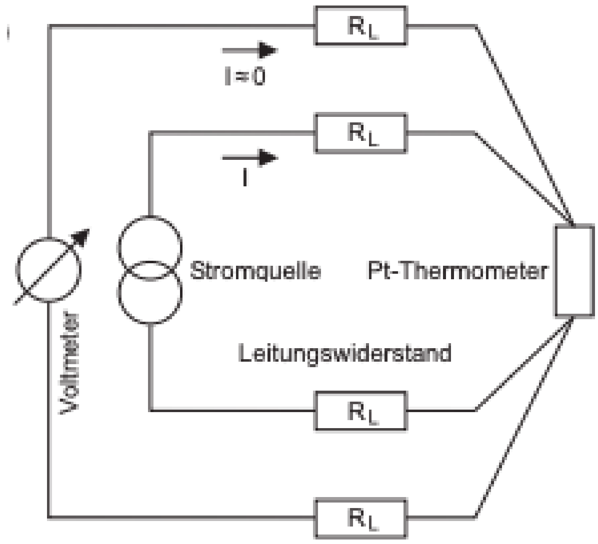

Figure 1: Four wire circuit

and white. This concept is for example used to approximate the temperature of planets. Everyday objects aren't usually completely opaque and black, which is why the Pyrometer shows a maximum emission capacity of $\varepsilon = 0.95$ instead of 1. One can measure the intensity distribution in dependance of the temperature and the wavelenght according to Planck's radiation law:

$$M_\lambda(\lambda, T)\,\mathrm{d}A\,\mathrm{d}\lambda = \frac{2\pi hc^2}{\lambda^5} \cdot \frac{1}{\mathrm{e}^{\frac{hc}{\lambda kT}} - 1}\,\mathrm{d}A\,\mathrm{d}\lambda \tag{5}$$

We can calculate the power emitted by a body with the Stefan-Boltzmann Law

$$P = \varepsilon(T)\sigma AT^2 \tag{6}$$

σ is the so called Setfan-Boltzmann constant. This power is based on the area and the temperature of an object. A Pyrometer works with this principle, it can measure temperature remotely by having an optical system reflect the radiation of an object back into a sensor, which then gets interpreted as the temperature in the reading.

3 Versuchsaufbau

3.1 Materialen und Geräte

- Pyrometer, with an accuracy of $\sigma_{T_P} = 2\,°\mathrm{C} \pm 1.5\%$

- Pt100 thermometer (class B), with an accuracy of $\sigma_{T_{Pt}} = 0.3\,^{\circ}\mathrm{C} \pm 0,5\%$
- Constant current source of $1\,\mathrm{mA}$
- Dewar flask
- Temperature bath
- Thermocouple for high temperatures (PtRh type S) with calibration table
- Multimeter, with an accuracy of $\sigma_V = 0,2\,\mathrm{mV} \pm 0,5\%$
- Gas Thermometer, translated into pressure with an accuracy of $\sigma_D = 1300\,\mathrm{mbar} \cdot 0.4\%$
- Butane gas bunsen burner
- Safetly glasses and protective gloves

3.2 Aufbau

4 Measurement and evaluation

4.1 Lab report

Lab report E41 Temperature measurement

Sep. 12, 2021

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Task 2:

We will measure the voltage difference, the pressure and the temperature of a glass balloon filled with air in different mediums over a wide range of temperatures. For that sometimes different equipment is needed.

Table 1: Voltage, Pressure and Temperature

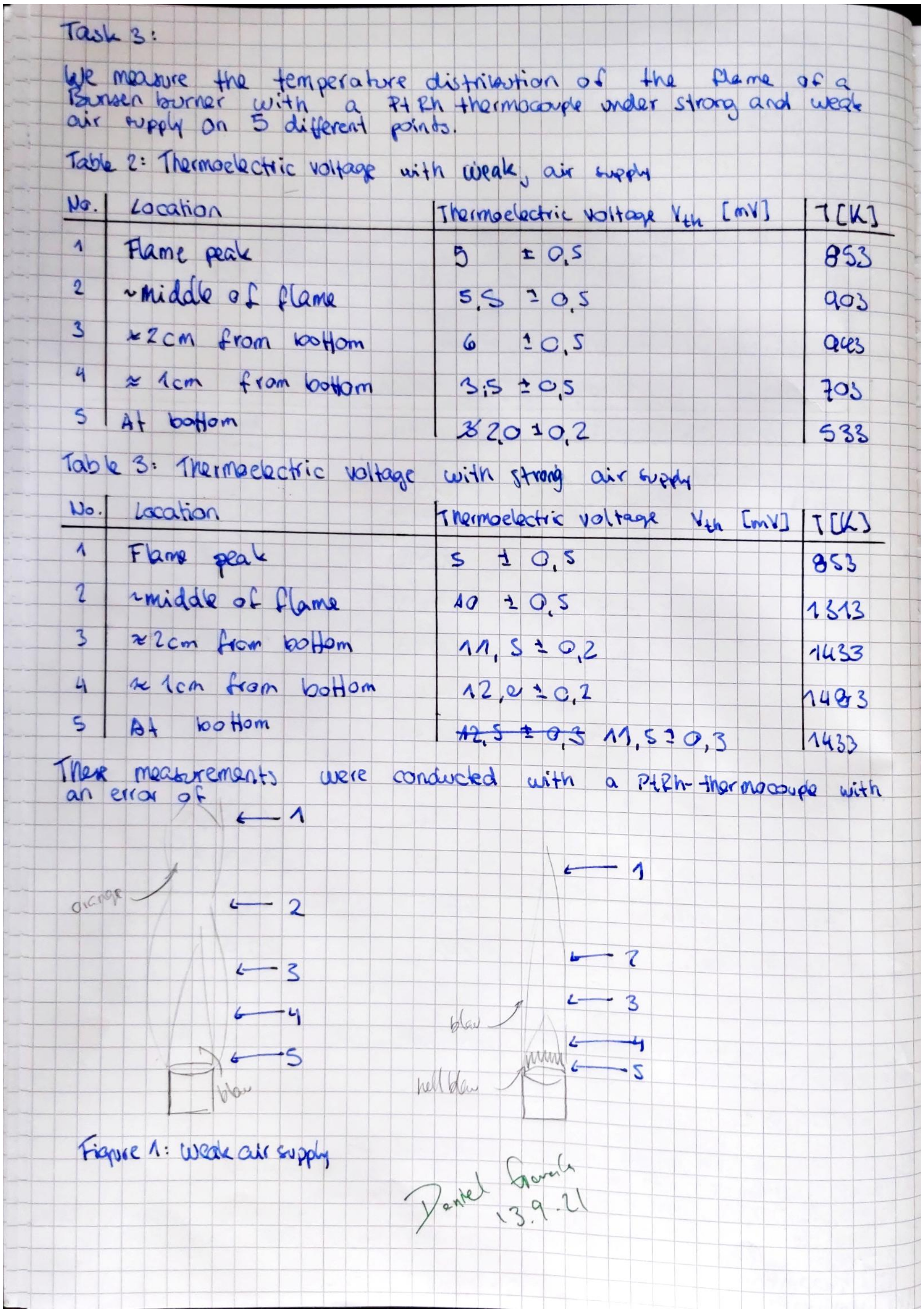
No.	Medium	Temperature T [K]	Pressure p [mbar]	Voltage V [mV]
1	Water-ice mixture	273,15	914	100,6
2	Water and hot-plate	288,15	965	105,3 ~~109,3~~
3		295,15 ~~294,15~~	1006 ~~995~~	110,0
4		303,15	1032	113,2
5		~~90~~ 313,15	1065	117,4
6		323,15	1098	120,9
7		335,15	1144	126,0
8		344,15	1171	129,5
9		353,15	1198	132,9
10		362,15	1242	138,1
11		368,15	1249	139,1
12	Dry ice and alcohol		661	71,1
13	Liquid nitrogen		249	26,9

After the measurements on the hot plate, we measure the atmospheric pressure to be

$p_{L0} = 1004,8 \pm$

For the measurements in the water-ice mixture and the hot plate we used a Pt100 thermometer and a pyrometer, which show an error of $\sigma_{Pt} = 0,3°C \pm 0,5\%$ and $\sigma_{Py} = 2°C \pm 1.5\%$ respectively.
For dry ice and alcohol and liquid nitrogen the pyrometer wasn't suitable.
The pressure was measured with a gas thermometer with an error of $\sigma_p = 1300 mbar \cdot 0,4\%$.
The Multimeter has an error of $\sigma_V = 0,2mV$; $0,5\%$.

Figure 2: Messprotokoll



Task 3:

We measure the temperature distribution of the flame of a Bunsen burner with a PtRh thermocouple under strong and weak air supply on 5 different points.

Table 2: Thermoelectric voltage with weak air supply

No.	Location	Thermoelectric voltage V_{th} [mV]	T [K]
1	Flame peak	5 ± 0,5	853
2	~middle of flame	5,5 ± 0,5	903
3	≈2cm from bottom	6 ± 0,5	953
4	≈ 1cm from bottom	3,5 ± 0,5	703
5	At bottom	~~3~~ 2,0 ± 0,2	533

Table 3: Thermoelectric voltage with strong air supply

No.	Location	Thermoelectric voltage V_{th} [mV]	T [K]
1	Flame peak	5 ± 0,5	853
2	~middle of flame	10 ± 0,5	1313
3	≈2cm from bottom	11,5 ± 0,2	1433
4	≈ 1cm from bottom	12,0 ± 0,2	1483
5	At bottom	~~12,5 ± 0,3~~ 11,5 ± 0,3	1433

These measurements were conducted with a PtRh-thermocouple with an error of

Figure 1: Weak air supply

Daniel Gravela
13.9.21

Figure 3: Fortsetzung Messprotokoll

4.2 Evaluation

4.2.1 Absolute zero

With the help of the two calibration points we analysed on water, the freezing point at 0 °C and the boiling point at 100 °C, we can draw a calibration line that cuts the x-axis at what's supposed to be absolute zero. Since the boiling point of water depends on the atmospheric pressure, we have to first adjust the measured value p_{Meas} at 95 °C to correspond to standard boiling point. We do this by using the measurement of the pressure outside $p_{LD}$and transforming with the help of the standard atmospheric pressure like this:

$$p_{NB} = p_{\text{Meas}} \cdot \frac{1013.25\,\text{mbar}}{p_L D} \quad (7)$$
$$= 1249\,\text{mbar} \cdot \frac{1013,25\,\text{mbar}}{1004.8\,\text{mbar}} \quad (8)$$
$$= 1259,5\,\text{mbar} \quad (9)$$

To determine the accuracy of this measurement, we use Gauss' error propagation law. The error on the measured pressure is of $\sigma_{p_{\text{Meas}}} = 5.2\,\text{mbar}$ and we consider a readout error of $\sigma_{p_{LD}} = 0,5\,\text{mbar}$, since we don't know the accuracy of the barometer in the hall. The only considerable error here is the measurment error, so we can assume the error of p_{NB} to be $\sigma_{p_{NB}} = 5.2\,\text{mbar}$. This value is too small to accurately portray on the graph paper, or to propose significant changes to the original line. From the intersection with the Temperature axis, we can infer that the absolute zero point can be found at around $T_0 = -270\,°\text{C}$. We will try to estimate an error here, firstly with the scale of the graph paper, in which one unit of lenghth represents 2 °C, secondly with our ability to properly plot the points in the desired places and draw a line between the two points, it is fair to assume that our error lies within a range of $\sigma_{T_0} = 3\,°\text{C}$. When we assign a temperature value on the line to the measured pressure of dry ice and liquid nitrogen, we get $T_{N_2} = (-194 \pm 2)\,°\text{C}$ and $T_{\text{Dry ice}} = (-74 \pm 2)\,°\text{C}$. If we use the literature value of the temperature of liquid nitrogen $T_{\text{Lit}N_2} = -195.8\,°\text{C}$, we get a nearly identical line, but this time the zero pressure point is at around

$$T_0 = (-272 \pm 3)\,°\text{C}\| \quad (10)$$

4.2.2 Correlation between resistance and temperature

To find a correlation between the resistance and the temperature, we first have to translate the measured pressure to its associated temperature on the calibrating line. We get the following values:

Nr.	Pressure p [mbar]	Temperature T [°C]	Resistance R [Ω]
1	914	0 ± 2	100.6 ± 0.7
2	965	14 ± 2	105.3 ± 0.7
3	1006	24 ± 2	110.0 ± 0.8
4	1032	33 ± 2	113.2 ± 0.8
5	1065	43 ± 2	117.4 ± 0.8
6	1098	53 ± 2	120.9 ± 0.8
7	1144	67 ± 2	126.0 ± 0.8
8	1171	74 ± 2	129.5 ± 0.8
9	1198	82 ± 2	132.9 ± 0.9
10	1241	94 ± 2	138.1 ± 0.9
11	1249	96 ± 2	139.1 ± 0.9

Table 4: Pressure, temperature and resistance

All of these values are faulted with a readout error of $\sigma_T = 2\,°\mathrm{C}$. With Ohm's Law we can also determine the resistance for the corresponding measurements. Because of the constant current of $I = 1\,\mathrm{mA}$, we can simply use the digits of the voltage and give them in Ω, e.g. $R_1 = \dfrac{100.6\,\mathrm{mV}}{1\,\mathrm{mA}} = 100.6\,\Omega$. Its error was calculated with a simple gaußian error propagation accounting for the error in voltage given by the Multimeter $\sigma_U = 0,2\,\mathrm{V} \pm 0.5\%$. The error of the pressure is still $\sigma_{p_{\mathrm{Meas}}} = 5.2\,\mathrm{mbar}$. We plot the values of Table 4 in a diagram and try to find a correlation between the resistance and the temperature. This yields a relatively linear relationship between them with a slope a of

$$a = \frac{\Delta R}{\Delta T} = \frac{31.25\,\Omega}{80\,°\mathrm{C}} = 0.390\,625\,\Omega\,°\mathrm{C}^{-1} \tag{11}$$

with an error according to the error line of

$$\sigma_a = \left| a - \frac{35\,\Omega}{80\,°\mathrm{C}} \right| = 0.05\,\Omega\,°\mathrm{C}^{-1} \tag{12}$$

meaning we get a slope of

$$a = (0,39 \pm 0,05)\,\Omega\,°\mathrm{C}^{-1} \tag{13}$$

The linear component of the polynomial to determine R is according to the course's script $R_0 \cdot A = 100\,\Omega \cdot 3.9083 \cdot 10^{-}3\,°\mathrm{C}^{-1} = 0.39083\,\Omega\,°\mathrm{C}^{-1}$. Comparing our slope and this value we get only a slight difference of

$$1 - \frac{0.39083\,\Omega\,°\mathrm{C}}{0.39\,\Omega\,°\mathrm{C}} = 0.0005 = 0.05\% \tag{14}$$

which shows how good of an approximation a linear approach for the temperature range is.

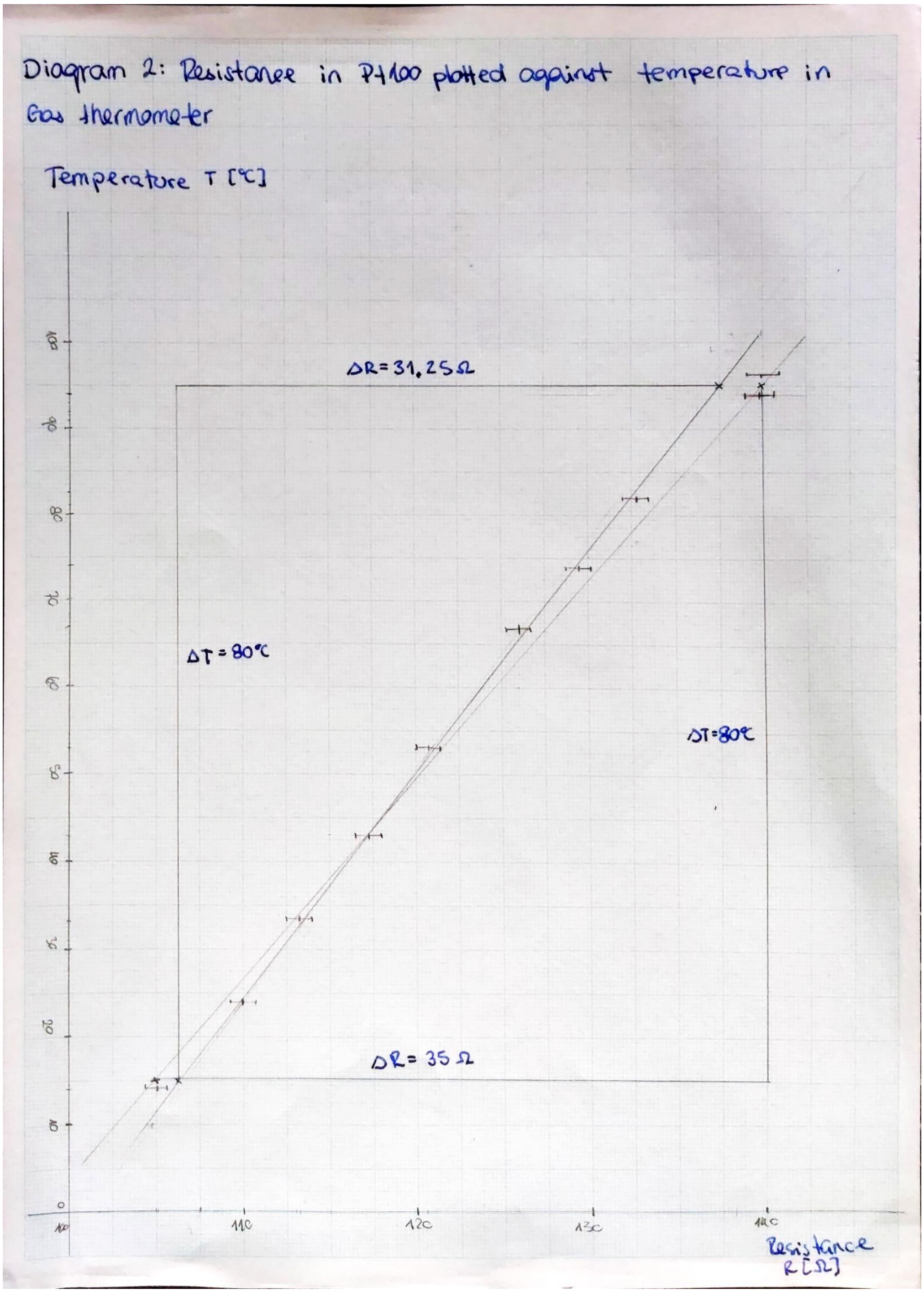


Diagram 1: Resistance and temperature

4.2.3 Temperature with Gasthermometer and Pyrometer

In the following we will plot in diagram 2 the temperatures measured with the Gasthermometer, (see Table 4) and the Pyrometer (see Table 1 on the lab report). First we have to readjust the values of the temperature in Table 1 back into Celsius, as the measurement was initially done in Kelvin to account for errors. The errors in table 5 were determined according to the error of the Pyrometer given in the lab report and for the Gasthermometer we used a readout error of 2 °C, which is the value of the smallest scale on the graphing paper.

Table 5: Temperature with Pyrometer and Gasthermometer

Pyrometer T_P [°C]	Gasthermometer T_G [°C]
0 ± 2	0 ± 2
11 ± 2	14 ± 2
22 ± 2	24 ± 2
30 ± 3	33 ± 2
40 ± 3	43 ± 2
50 ± 3	53 ± 2
62 ± 3	67 ± 2
71 ± 3	74 ± 2
80 ± 3	82 ± 2
89 ± 3	94 ± 2
95 ± 3	96 ± 2

If we take a look at diagram 2, we can see that the line is offset by about +2 °C on the Gasthermometer, and that the Pyrometer shows aroud 95% ± 12% the temperature of the Gasthermometer. Ideally, the ratio would be 1 : 1 and the line would go through the origin.

4.2.4 Thermocouple

Finally, we assigned a temperature value to the measured voltage using the calibration tables at our disposal. The table is only accurate for specific temperatures, to estimate an error we take a look at our estimated error on the voltage and compare with the values on the extremes of the temperature. For that we will include the error in table 6.

Contrary to what we would have initially expeceted, the highest temperatures aren't near the bottom, but a few centmeters above.

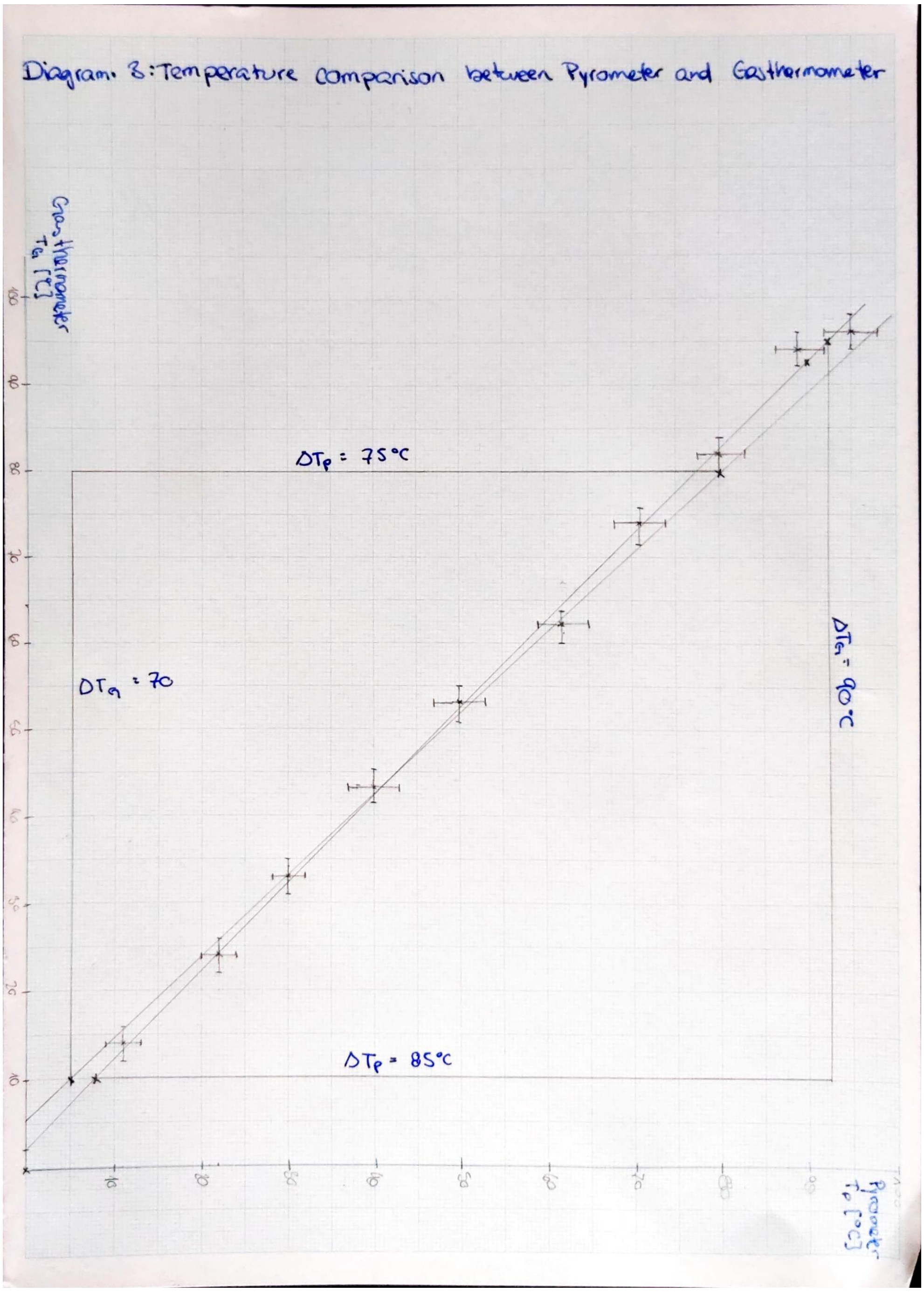


Diagram 2: Temperature with pyrometer and gasthermometer

Table 6: Temperature with Pyrometer and Gasthermometer

No.	Air supply	Location	Voltage U_{th} [mV]	T [K]	σ_T [K]
1	weak	Flame peak	5.0 ± 0.5	853	50
2		Middle of flame	5.5 ± 0.5	903	50
3		≈ 2 cm from bottom	6.0 ± 0.5	943	50
4		≈ 1 cm from bottom	3.5 ± 0.5	703	50
5		At bottom	2.0 ± 0.2	533	30
1	strong	Flame peak	5.0 ± 0.5	853	50
2		Middle of flame	10.0 ± 0.5	1313	50
3		≈ 2 cm from bottom	11.5 ± 0.2	1433	30
4		≈ 1 cm from bottom	12.0 ± 0.2	1483	30
5		At bottom	11.5 ± 0.3	1433	30

5 Conclusion and discussion

5.1 Conclusion

We learned the basics of how four different kinds of thermometers work. Since a lot of physical quantities are somehow related to temperature, we can indirectly measure it through many different ways. We performed the measurements in extremely cold, regular and really hot temperatures with the adequate equipment for each of these conditions. The four thermometers we used were 1. the Gasthermometer, which is based around the ideal gas equation, from which we can measure the pressure and assign it a temperature value by keeping the volume constant, 2. the thermocouple, which is based on the seebeck effect, according to which a temperature difference between two connected dissimilar conductors produce an electric voltage, 3. the resistance thermometer, in which the resistance changes with the temperature according to the polynomial in (3), but for which a linear approximation is still pretty accurate in the temperature range we observed and lastly the Pyrometer, which detects the infrared radiation emitted from a body, which is correlated to the temperature of the body as per the black body radiation.

5.2 Discussion

Each of the thermometers had its own advantages and disadvantages. The gas thermometer required only two simple measurements to somewhat accurately predict the absolute zero of temperature at around $T_0 = (-270 \pm 2)\,°\mathrm{C}$. Although the real value isn't exactly in the range we predicted, it is still close enough to find the result satisfactory, a comparison yields a deviation of

$$\frac{-270\,°\mathrm{C} + 273.15\,°\mathrm{C}}{2\,°\mathrm{C}} = 1.6 \tag{15}$$

1.6 σ, which although improvable, lies within the acceptable area. However, a disadvantage of this method is that a calibration lines is needed in the first place, and by only having two reference points, it is very susceptible to small mistakes, which can falsify the result. We also had to graphically determine the temperature in the intervall between freezing and boiling, and without an appropriate scale, this method leads to great errors. With the calibration line we were also able to interpolate the temperature of the liquid nitrogen and the dry ice mixture by assigning a value to the pressure in these mediums, since none of our other instruments had a range wide enough to tell such low temperatures. The value for liquid nitrogen was as well somewhat accurate, deviating from the literature value by only 1.8 °C, with a total deviation of

$$\frac{195.8\,°\mathrm{C} - 194\,°\mathrm{C}}{2\,°\mathrm{C}} = 0.9 \tag{16}$$

0.9 σ.

The thermocouple is useful for measuring temperatures at which the rest of the instruments can't accurately make predictions, but it is however very inaccurate, showing deviations of up to 50 K from the expected. This is also due to uncontrollable circumstances, like the sudden movement of the flame and the drastic changes in temperature in the point where we were measuring it. It is however, a very good tool to roughly estimate the temperature, for practical purposes, it's not as relevant if the bunsen burner has a temperature of 1400 K or 1450 K. The thermocouple allowed us to qualitatively describe the temperature composition of the flame at high and low air supply. Namely, the temperature is highest not at the bottom, but a couple of centimeters above towards the center. This is likely because the gas isn't immediately burned upon exit, but the maximum burn is reached after the gas has reached an efficiency maximum.

The linear approximation for the Pt100 thermometer was surprsingly good, showing a mere 0.05% deviation from the linear term of the polynomial. However, by doing manual work such as drawing lines through points and visually estimating where the line should be, many things are left to chance. It is hard to tell to what extent this result is work of the measurements, of the ability to properly draw the line or simply coincidence.

Lastly, we compare the pyrometer with the gas thermometer. For the convenience of measuring the temperature remotely and without laborious equipment, it shows many advantages over the rest of the instruments. Especially for use that doesn't require high levels of precission. A fault of this instrument is the susceptibility to many systematic errors. For starters, it assumes a constant emission capacity of $\varepsilon = 0.95$ and it also requires a somewhat competent usage. Pyrometers were widely spread out during the Corona-Pandemic to check temperatures of people before entering an establishment, for example in countries such as Mexico. While in principle a good preemptive measure, a difference in 2 °C when checking the body temperature is quite significant, and since most people aren't using the pyrometer correctly, e.g. pointing it at the incorrect distance, it fails to fulfill its purpose effectively. Anecdotal evidence of checking each other's temperature during the execution of the experiment, and consistently getting values under 34 °C would suggest that we were suffering from a severe case of hypothermia and close to death. We are luckily all still alive and well, so it would appear that the instrument has a vital flaw there. When used it should be taken into consideration that it comes with a great inaccuracy.

6 Sources and further literature

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