Experiment No. 50

Temperature measurement

Keywords:
Temperature, temperature scales (Celsius, Kelvin), fixed points, Thermometers: (gas, liquid thermometers, thermocouples, resistance thermometers, pyrometers, thermo-indicators) Zeroth law of thermodynamics, thermoelectric- (Seebeck-) effect, cold mixtures

Literature:
Atkins "Physical Chemistry"
Kohlrausch "Practical Physics", Volume 1
Gerthsen, Kneser, Vogel "Physics"
Jander, Blasius "Textbook of analytical and preparative inorganic chemistry"

Basics:
Temperature is a state variable, i.e. every system that is in thermal equilibrium can be assigned a unique value for the property "temperature". As experience shows, all systems that are in thermal equilibrium with a given system are also in thermal equilibrium with each other. They then have the same temperature. This relationship is also known as the "zeroth law of thermodynamics" and forms the basis of temperature measurement.
The temperature scale required for this is obtained by bringing a suitable thermometer into thermal contact with systems of different temperatures and allowing thermal equilibrium to be established. Then a suitable variable of the thermometer that depends on the temperature is measured (e.g. the length of a liquid column, the electronic resistance, the volume of a gas, the thermoelectric voltage) and the change in this variable with temperature is empirically determined.
A linear calibration function is particularly advantageous, but not a requirement.
A temperature scale can be set quite arbitrarily.
The Celsius scale uses two fixed points: the melting point of ice (0 °C) and the boiling point of water (100 °C), both at an external pressure of 1 atmosphere.
In order to be independent of the thermal properties of the materials used to measure the temperature, the thermodynamic temperature scale was introduced.
The definition of this scale is based on the consideration of a Carnot-Cycle. In 1848, W. Thomson, later known as Lord Kelvin, recognized that this meant that an absolute temperature scale existed. In his honor, the temperature unit is called Kelvin (K).
Its zero point is called absolute zero, and the temperature measured from this zero point is called absolute temperature.
The size of the Kelvin and the reference point of the Kelvin scale were defined in 1954 so that the temperature of the triple point of water (see section on vapor pressure of liquids, Fig. 1) is exactly 273.16 K.
There is a simple additive relationship between the mandatory SI unit 'Kelvin' and the 'degree Celsius' that is still used in practice:

(1) $$T\,[K] = t\,[°C] + 273.15$$

where a capital T is always used for the Kelvin and a small t for the degree Celsius.
Since both units only differ by an additive constant, the symbol grd is often used for both units when specifying temperature differences and in dimensional considerations.

Some important temperature measuring devices are discussed below:
The gas thermometer is an important device for measuring thermodynamic temperatures in a wide temperature range, e.g. when using helium from about 3 K to almost 1900 K.
It is based on the empirically found state relationships of (ideal) gases (Gay-Lussac's laws):

- at constant volume, the pressure is proportional to the absolute temperature

(2) $p_1 / T_1 = p_2 / T_2$

- at constant pressure, an (ideal) gas expands by around 1/273 of its volume at 0 °C when heated by 1 grd:

(3) One commonly still used thermometer fluid is mercury.
Its advantages are the almost linear relationship between its density and temperature and the low vapor pressure (2 μbar at room temperature).
The application range of the mercury thermometer is limited at low temperatures by the freezing point at t = -38.8 °C and at high temperatures by the strong increase in vapor pressure. "High-graded" mercury thermometers (for temperatures from 300 to 600 °C) always contain an inert gas (nitrogen or argon) above the mercury, with pressure which are higher than the vapor pressure of the mercury at the highest operating temperature.

Only non-metallic thermometer liquids, to which a dye is often added, can be used to measure low temperatures:
Toluene is suitable for temperatures down to -90 °C,
ethanol down to -110 °C and
pentane down to -130 °C.
Although these organic substances have a considerably larger cubic expansion coefficient than mercury, they have poorer thermal conductivity and wet the glass. This leads to the liquid thread breaking off more often than with mercury thermometers.

Bi-metal thermometers use the different temperature-dependent linear expansion of metals and have many technical applications (e.g. hotplates, irons, etc.) For continuous temperature measurements and measurements in places on equipment that are not easily accessible, thermometers are used whose functionality allows the use of electrical measuring methods.
For example, the temperature dependence of the electrical resistance of metals and semiconductors can be used in resistance thermometers. The resistance is often measured using a “Wheatstone bridge” for this purpose. In contrast to metallic conductors, the number of charge carriers in semiconductors increases significantly when the temperature increases.
This effect outweighs the obstruction of the charge carriers by the lattice vibrations.
In contrast to metals, semiconductors therefore have a falling resistance characteristic (NTC = negative temperature coefficient).

Of the electrical thermometers, thermocouples are the most commonly used for temperature measurement. They are very easy to manufacture, have a very small spatial dimension, are relatively free of inertia and are particularly suitable for measuring temperature differences.
Their mode of operation is based on the thermoelectric effect (Seebeck, 1822), which explains the creation of electrical voltages due to temperature differences at the contact points between two different metals (see Fig. 1).

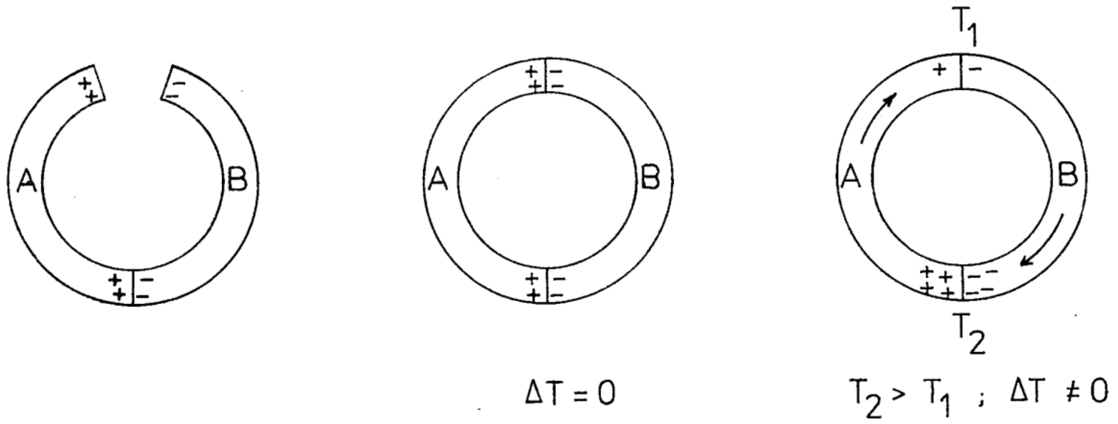

Fig. 1: Seebeck effect: Contact voltage on two metals in contact. Thermoelectric voltage due to temperature difference.

The following applies:
When two different metals touch, some electrons flow from the metal with the smaller electron work function (metal A) to the metal with the larger work function (metal B). This causes metal A to be positively charged compared to metal B.
This thermoelectric voltage can be measured with a high-resistance millivoltmeter.

For certain metal A/metal B combinations, it changes linearly with the temperature difference between the contact points.
An ABA combination has the advantage of comparing the temperatures between the contact points AB and BA. It is advisable to set one of the contact points, e.g. BA, to the reference temperature 0°C (Fig. 2). The change in thermoelectric voltage with temperature is referred to as the sensitivity or "thermopower" of the thermocouple. It is in the order of 10^{-5} volts per degree.

Common metal combinations are copper/constantan, iron/constantan, platinum/rhodium or nickel-chromium/nickel. (Constantan is a copper-nickel alloy (60% Cu)).

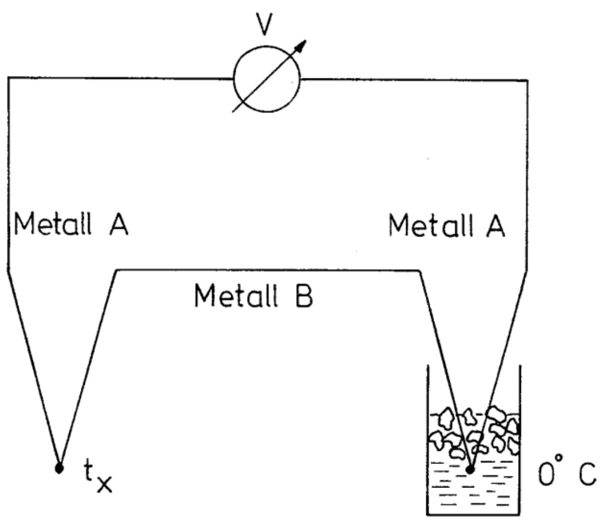

Fig. 2: Temperature measurement with thermocouples

Another important group of thermometers are radiation thermometers (pyrometers). These compare the intensity of the thermal emission of the test body with the intensity of a light source whose temperature is known.
Radiation thermometers can be used to measure very high temperatures (> 800 °C) because the hot body does not need to be touched during the measurement.

Temperatures below 0°C can be achieved in the laboratory using cold mixtures.
By mixing salts that have a negative heat of solution with water or crushed ice, the temperature of the solution drops if no heat is supplied from the outside. The achievable temperature reduction also depends on the ratio of the mixed substances.

Certain low temperatures can be set when evaporating low-boiling liquids.

Task:
Using liquid thermometers, calibrate

a) a nickel/chromium-nickel thermocouple in the temperature range between -200 °C and +100 °C.
b) a semiconductor resistance thermometer in the temperature range between 0 °C and +100 °C
c) a platinum resistance thermometer between 0 and 100 °C.

On the experimental setup:
The following cold/heat baths are prepared in Dewar vessels:

1) Liquid nitrogen * -200 °C
2) ethanol (cooled with liquid N_2) -110 °C
3) ethanol / dry ice - 80 °C
4) ice / salt (in the large Dewar vessel) - 20 °C
5) ice / water 0 °C
6)- 10) water baths of different temperatures in the range between 0 °C and +100 °C

Procedure:
1) Prepare an ice/water bath, then prepare the other cold baths in consultation with the second group.
2) Set up the circuit for temperature measurement with the thermocouple and ensure the polarity is correct (see Fig. 2)
3) When measuring the bath temperature, always hold the thermometer in the middle of the cold/heat bath. Read the display of the liquid thermometer and the electrical instrument at the same time.
4) Repeat 2) & 3) accordingly for the temperature measurements with the semiconductor (see Fig. 3) and the platinum resistor (correspondingly).

IMPORTANT:
- Only use the wooden stick for stirring!
- Handle the Dewar vessels very carefully!
- Do not cool the semiconductor below 0 °C!

* The temperature of liquid nitrogen in [K] is calculated from the measured air pressure p [Torr] using the following equation:

$$\ln p = -663\,[K] / T + 15.2$$

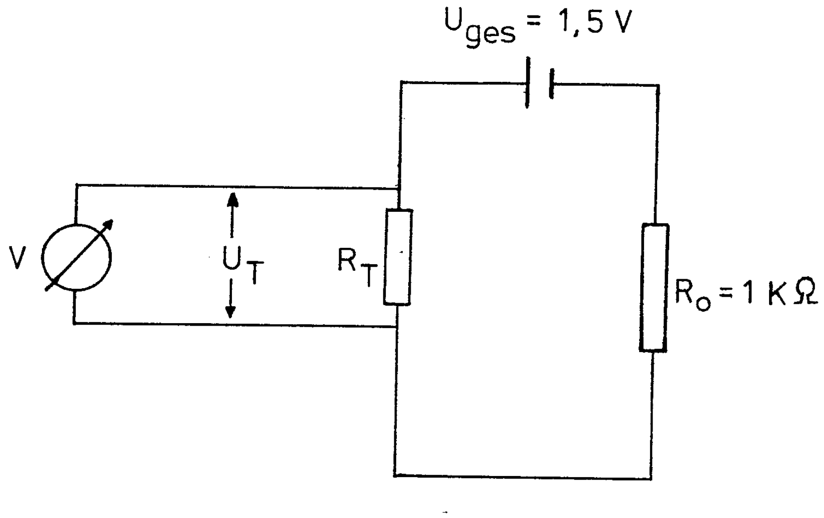

Fig. 3: Circuit diagram for temperature measurement with an NTC resistor

The following applies to the NTC resistor R_T: (4) $R_T = R_0 \bullet U_T / (U_{ges} - U_T)$ (why?)

Evaluation:

1) Plot on millimeter paper:

a) the thermoelectric voltage as a function of the temperature of the liquid thermometer

b) the resistance of the semiconductor as a function of the temperature of the liquid thermometer

c) the logarithm of the resistance of the semiconductor as a function of the temperature

d) the resistance of the platinum resistor as a function of the temperature

2) Discuss these calibration curves!

3) How large is the thermoelectric power of your nickel / chromium nickel thermocouple? Compare with literature values!

Accessories:

8 Dewar vessels, thermocouples, semiconductors, microvoltmeter, circuit for resistance measurement, 3 liquid thermometers (+30 to -100 °C), wooden stick, test cable, platinum resistor (PT100)