THEORY

Temperature is a state variable indicating whether or not an object is in thermal equilibrium with its environment. Of course, it is a function of other state variables of the object. Temperature can be measured so that we choose one of these properties which is easy to measure and a one-to-one function of temperature.
To assign a numerical value to the temperature we have to scale the measured value (e.g. volume, resistance, radiation, etc.). Choosing a working material and a property, with an arbitrary scale we get an empirical temperature. The thermodynamic temperature scale is based on the second law of thermodynamics (the efficiency of the Carnot engine).

The properties of a good thermometer are:
- small heat capacity (it does not change the temperature to be measured) ,
- small inertia (it reaches the thermal equilibrium fast),
- good reproducibility.

Thermometers can be grouped in the following way:
1.) The thermometer and the object with unknown temperature are not in direct connection. These are pyrometers for measuring high temperatures (above ~500°C) based on the thermal radiation.
2.) The thermometer and the object are in direct connection. These are mechanic and electric thermometers:

2.A.) Mechanic thermometers:
- Metal rod thermometer. The linear thermal expansion is measured.
- Bimetallic thermometer. Two strips of metals with different coefficients of linear expansion (e.g. brass and iron) are riveted together. When heated, the strip bends, when cooled, the coil opens up.
- Liquid-in-glass thermometers. The liquid may be ethanol, mercury or pentane. The expansion of the liquid in the reservoir can be read on the linear scale of the capillary joining with the reservoir.
- Mercury (liquid)-in-steel thermometer. Here the liquid is expanding in a flexible spiral tube the shape of which depends on the temperature.
- Vapour pressure thermometer. A suitable liquid is placed in a bulb and connected to a pressure gauge which is used graduated for temperature.
- Gas thermometer. The pressure in constant volume conditions (or volume in constant pressure conditions) is proportional to the thermodynamic temperature (supposing that the gas is ideal).

2.B.) Electric thermometers:

2.B.1) Thermoelectric thermometer, thermocouple.
When two different metals join, an electric potential difference will occur at the junction point. This contact potential depends on the two materials and on the temperature. In a closed circuit the sum of these contact potentials equals to zero if the temperature of all joining points is equal. But if the joining points have different temperatures then a thermoelectromotive force is generated this way.

2.B.2) **Resistance thermometers**.
Resistance thermometers are made of
a) metals,
b) semiconductors (called thermistors).

a) The resistance of **metals** is a linear function of the temperature:

$$R(T) = R_0 \left(1 + \beta (T - T_0) \right) ,$$ where

R_0 is the resistance at the reference temperature T_0 ,

β is the temperature coefficient [1/C°] or [1/K]
that can be considered constant for a certain temperature range.

The sensitivity of metal resistance thermometers is this constant: $\frac{1}{R_0} \frac{\Delta R}{\Delta T} = \beta$

The metals used for resistance thermometers are mainly Ni or Pt.

Their **inertia** is relatively great.

b) In case of **semiconductors** the resistance is a nonlinear function of the temperature, that is β cannot be considered constant. Thermistors have greater sensitivity and smaller inertia than metal resistance thermometers have.

The inertia of thermometers

When the temperature of the thermometer's environment suddenly changes then the thermometer approaches this new value gradually.

The process can be described by the following equation (Newton's equation):

$$\Delta T(t) = \Delta T_0 \cdot e^{-\frac{t}{\tau}}$$, where

ΔT is the temperature difference **between the thermometer and its environment** at the time instant t,

ΔT_0 is the initial temperature difference (at $t_0 = 0$), and

τ is the time constant of the thermometer.

At $t = \tau$ $\Delta T(\tau) = \Delta T_0 / e$.

The time constant τ depends on

- the heat capacity of the thermometer C , and
- the surface of the thermometer (through which the heat transport happens) A , and
- the heat transport coefficient between the thermometer and the environment α :

$$\tau = \frac{C}{A\alpha}.$$

Instead of τ sometimes $t_{1/2}$ (the half-time) is used: at $t = t_{1/2}$ $\Delta T(t_{1/2}) = \Delta T_0 / 2$.

With this constant the Newton equation is: $\Delta T = \Delta T_0 \cdot 2^{-\frac{t}{t_{1/2}}}$

MEASUREMENT

We shall measure temperature-fall and -raise curves with a Pt resistance thermometer. The resistance is measured with a digital multimeter.

First measure the temperature-fall curve:

Check that the resistance of the thermometer is constant in the thermostat. Then as fast as possible put the thermometer into the jar of water with ice cubes and record the resistance as a function of time, at the time instants indicated in the table (data sheet).

Measure the temperature-raise curve in a similar way.

EVALUATION

1. Calculate the temperature at every time instant from the resistance using the formula

$R(T) = R_0 (1 + \beta (T-T_0))$, where

T_0 is zero (the temperature of water with ice),

R_0 is the resistance measured in the water with ice, and

the value of the temperature coefficient is $\beta = 0.00386$ 1/C° .

The temperature of the thermostat T_{therm} is calculated from the resistance R_{therm}.

2. Calculate ΔT for the temperature fall and raise curves: $\Delta T_{fall} = T - T_0$, and $\Delta T_{raise} = T_{therm} - T$.

3. Plot the two ΔT *vs.* t graphs.

4. Determine the two time constants τ_{fall} and τ_{raise}:

a) find τ with fitting an exponential function using the formula $\Delta T = \Delta T_0 \cdot e^{-\frac{t}{\tau}}$;

b) linearize the formula, calculate the slope using Excel, and calculate τ from the slope.