Department of Physics and Biophysics; Institute of Biology

First name ....

Last name ....

Date ....

Degree program name ....

Exercise 375

Investigation of the dependence of thermal radiation on temperature

R_0 =								
	U [V]	I [mA]	R [□]	R/R_0	T [K]	P [W]	ln(T)	ln(P)
1.								
2.								
3.								
4.								
5.								
6.								
7.								
8.								
9.								
10.								
11.								
12.								

slope of the straight line $\ln(P) = a\cdot\ln(T) + b$	a =

Introduction

All objects, that have temperature greater than absolute zero, emit **thermal radiation.** Thermal radiation is an energy transfer as heat, through the emission or absorption of electromagnetic waves. It is generated by the thermal movements of charged particles in matter when part of the kinetic energy of these particles is converted into energy of the emitted waves. The energy of electromagnetic radiation varies over a wide range, depending on wavelength: a shorter wavelength (or higher frequency) corresponds to a higher energy.

The spectrum of radiation, i.e. how long and how many waves are sent, depends on the body temperature. Infrared radiation (wavelength: 750 nm - 1 mm) dominates the spectrum of bodies with a moderate temperature (e.g. room temperature). As the temperature increases, the emission of shorter wavelengths increases. In visible light (range of 390 - 750 nm) wavelength determines colour – red has the longest wavelength and violet the shortest. Therefore, for example, metals can be heated "to whiteness", that is, to such a high temperature that a large number of light waves of different colours appear, which when mixed give the impression of white light.

A Blackbody radiator is defined as an object that absorbs all electromagnetic radiation that falls on it at all frequencies over all angles of incidence. No radiation is reflected from such an object. The blackbody radiator also emits radiation in the entire range of electromagnetic waves. An important property of a blackbody radiator is that its total radiant energy is a function only of its temperature; that is, the temperature of a blackbody radiator uniquely determines the amount of energy that is radiated into any frequency band. (Fig. 1).

The total power radiated we define as the amount of energy emitted in the form of electromagnetic waves by the body per 1 second, also depends on the body temperature. The dependence of power on temperature was derived for the so-called blackbody and is called the **Stefan-Boltzmann law:**

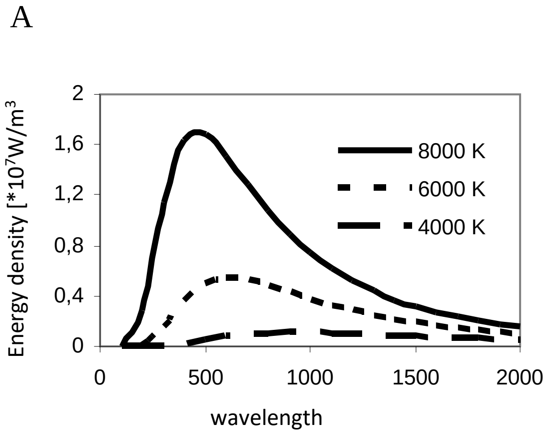
$$P = \sigma \cdot T^4 \tag{1}$$

$$\left[\frac{W}{m^2} = \frac{W}{m^2 \cdot K^4} \cdot K^4\right]$$

According to this law, the total radiation power P (per square meter of body surface) over the entire wavelength range is directly proportional to the fourth power of the body temperature T that it emits. The temperature here is expressed in Kelvin (T[K]=t[°C]+273). The symbol σ denotes the Stefan-Boltzmann constant, which for a blackbody is $\sigma = 5{,}6704 \cdot 10^{-8} \frac{W}{m^2 \cdot K^4}$.

Objects that are not perfectly black, absorb some wavelengths and reflect some wavelengths. The colour of objects indicates that light is reflected of a certain wavelength or a mixture of waves that produces a given colour. For , σ (Stefan-Boltzmann constant) is not constant as it depends on the length of the emitted wavelengths.

At high temperatures, most bodies radiate so that they can be interpreted as black bodies.



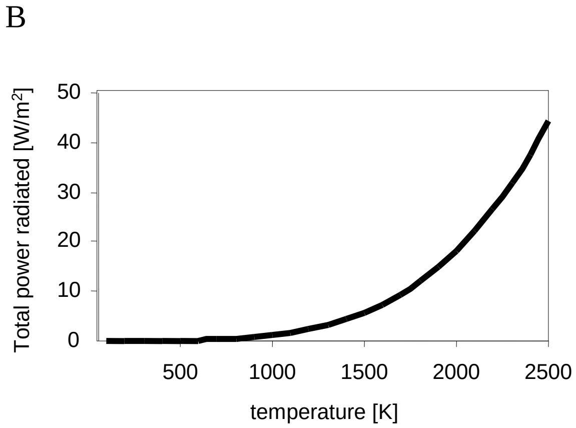


Fig.1 **A.** A graph of spectrum of electromagnetic waves emitted from blackbody radiator at three different temperatures. The energy density here describes the amount of radiation of a given wavelength emitted by the body. **B.** Stefan-Boltzmann law. Graph B can be obtained from graph A because the rate of radiation emission for each temperature value (B) is equal to the area under the energy density versus wavelength graph for the given temperature (A).

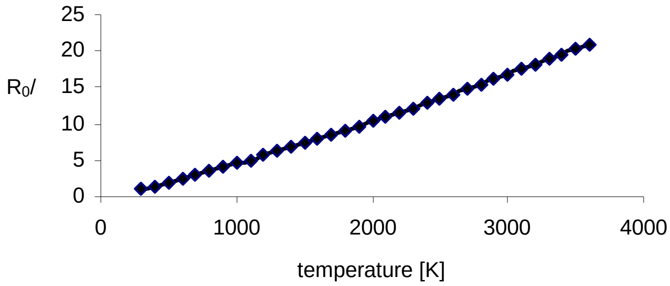
The graph of the dependence of the thermal energy on the temperature (Fig. 1B) can be presented as a linear function y = ax + b, if we naturally logarithm the equation (1). Then:

$$\ln(P) = 4\ln(T) + \ln(\sigma) \tag{2}$$

where y = ln(P), x = ln(T). The exponent of the power of 4 becomes after logarithm the slope of the linear function *a*.

In the exercise, dependence of radiation power on examples, tungsten light bulb filament. The flow of current through the tungsten filament causes its temperature to rise significantly. The lighting that we use in light bulbs is the result of the tungsten filament heating up. To change the temperature of the bulb, we will use the relationship between the intensity of the current and the amount of heat emitted by the conductor, because according to Joule's first law (also just Joule's law) $P = R \cdot I^2$ - the power of heating generated by an electrical conductor equals the product of its resistance R and the square of the current I.

The current can be adjusted by setting different voltages in the power supply. However, to measure the temperature of a bulb, we will use the fact that tungsten, like any metal, has a temperature-dependent electrical resistance: the higher the temperature, the greater the resistance. The dependence of resistance on temperature for most metals at low temperatures (in the range 0 - 100 ° C) is with high accuracy linear, but at high temperatures, it becomes curvilinear and can be approximated by a second-order polynomial: $R = R_0(1 + \alpha \cdot (T - T_0) + \beta \cdot (T - T_0)^2)$, where R - resistance at temperature T, R_0 - resistance at temperature T_0 (as T_0 we take the room temperature), α i β are the temperature coefficients of resistance. For tungsten, the dependence of resistance on temperature was determined experimentally (Fig. 2) and on this basis, the equation for temperature T as a function of R/R_0 was determined:



$$T = 121K + 198K\frac{R}{R_0} - 1{,}6K\left(\frac{R}{R_0}\right)^2 \qquad (3)$$

Fig.2 Dependence of R/R_0 on temperature T for tungsten. R - resistance at temperature T, R_0 - resistance at temperature T_0 = 293 K.

We calculate the resistance *R* on the basis of Ohm's law, which says that the current I is directly proportional to the applied voltage U:

$$U = I \cdot R \qquad (4)$$
$$[V = A \cdot \Omega]$$

That is:
$$R = \frac{U}{I}$$
$$[\Omega = V / A]$$

According to Ohm's law, the resistance is constant and does not depend on the current intensity.

The power of thermal radiation can be determined assuming that the entire energy of the current flowing through the bulb is converted into heat and is radiated to the environment in the form of electromagnetic waves. The power of thermal radiation can be determined assuming that the entire energy of the current flowing through the bulb is converted into heat and is radiated to the environment in the form of electromagnetic waves. Then the radiation power will be equal to the current power, which we can calculate from the formula:

$$P = U \cdot I \qquad (5)$$
$$[W = V \cdot A]$$

Where *P* - the power of the current, *U* – the voltage applied to the light bulb, *I* - the amount of current flowing through the light bulb.

Performance of the task

1. The electric circuit inside the box consists of a regulated power supply and a light bulb. We connect electrical meters to the circuit: an ammeter (mA) in series with the light bulb, a voltmeter (V) in parallel with the bulb (Fig. 3). In the ammeter, one cable is connected to the COM socket, and the other to the mATEMP socket. Set the rotary switch to mA. Use the DC / AC button to select DC, i.e. direct current. In the voltmeter, one cable is connected to the COM socket, the other to the VΩHz socket. Set the rotary switch to V DC.

A. 

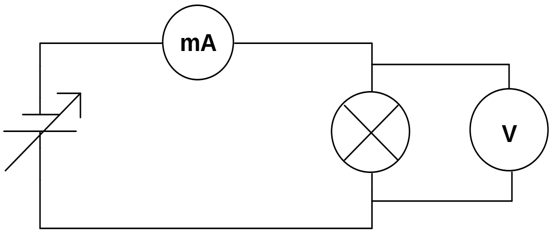
B. 

Fig.3 **A.** Experimental setup. **B.** Schematic diagram of the electrical connections.

2. In the measurement table, write down the resistance of the bulb at room temperature R_0 (the value is given on the box).
3. Turn on the power supply and record the voltmeter and ammeter readings for the twelve settings of the power supply knob. After each change of power supply, wait about 20 seconds for the bulb temperature to stabilize.
4. For each of the twelve measurements to calculate:
    - from formula (4), resistance R, then ratio,
    - from formula (3), the temperature T of the bulb filament
    - from formula (5) the power P absorbed by the bulb,
    - from formula ln (the natural logarithm) from the values of T and P (scientific calculator needed).
5. On an A4 sheet of paper, draw a graph of the dependence of ln (P) on ln (T). The graph should show a linear function which is described by the equation y = ax + b (formula (2)).
6. Mark any two points "i" and "j" located on the straight line (Fig.4) (select points as close as possible to the beginning and end of the straight line). Read the coordinates of ln (P) and ln (T) of these points. From the pattern

$$a = \frac{\ln(P_i) - \ln(P_j)}{\ln(T_i) - \ln(T_j)}$$

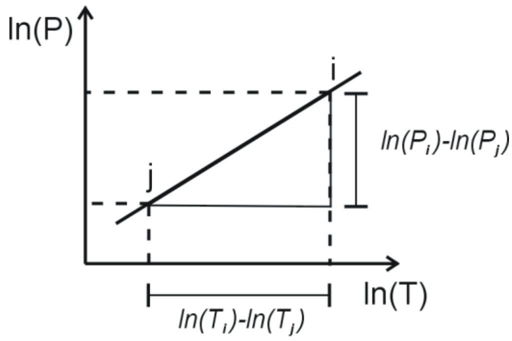


Fig.4 Determination of the slope coefficient of the linear function

calculate the slope of the line *a* with accuracy to three meanings of numbers.

9. Calculate the percentage difference between the theoretical (equal to exactly 4) and the experimental value of the slope of the straight line.

Calculation of the uncertainties

Calculate the relative error of determining the slope of line *a* from the formula:

$$\frac{\Delta a}{a} = \left(\frac{\Delta U}{U} + \frac{\Delta I}{I} + \frac{\Delta T}{T} \right)$$

where $\frac{\Delta U}{U}$ - relative voltage measurement error (accuracy of the voltmeter 1%), is the relative error of the voltage measurement (voltmeter accuracy 1% $\frac{\Delta I}{I}$ - the relative error of the current measurement (accuracy of the ammeter 1 %), $\frac{\Delta T}{T}$ - the relative error in determining the bulb temperature (4%) (the accuracy of this value consists of the accuracy of the bulb resistance measurement and the accuracy of the formula (3) from which we calculate the bulb filament temperature.

Questions for discussion

1. Is the Stefan-Boltzmann law fulfilled for the light bulb? Justify your answer (compare the percentage difference of the slope coefficient between the theoretical and experimental value - the value calculated in point 9 - with the relative error of determining the slope coefficient - the value calculated in point 10).
2. Is Ohm's law fulfilled for the light bulb? Justify your answer.
3. What mechanisms of energy dissipation from the light bulb, other than radiation, were omitted in the exercise? How can they affect the outcome of the exercise?