27. Verification of Stefan-Bolzmann`s law. Determination of Stefan-Bolzmann`s constant.

Assignment

1. Verify the Stefan-Boltzmann`s law.
2. Investigate the influence of the fit using your measured data on the accuracy of the result.
3. Measure the value of the Stefan-Bolzmann`s constant by the pyrometer
4. Summarise your findings and discuss the source of errors in this experiment.

Theoretical part

An object emits radiation at any temperature referred to as thermal radiation. This radiation depends on the temperature and properties of the object. All objects radiate the energy continuously in the form of electromagnetic waves.

The total amount of the thermal radiation emitted per second per area of the body is proportional to the fourth power of the body's temperature. This law is called *Stefan-Bolzmann's one* and is given by the expression

$$P = \varepsilon \sigma T^4 \qquad (12.1)$$

where σ is called as *Stefan-Bolzmann's constant*. Its value equals 5.6696×10^{-8} W.m^{-2}.K^{-4}, T is the temperature of the radiated object in Kelvins and ε is the constant called as *emissivity*.

The emissivity depends on the nature of the radiating surface. For a perfect reflector, which does not radiate at all, is $\varepsilon = 0$. A blackbody has the coefficient of emissivity equal 1. For example, for oxide copper its value is 0.6, for oxide nickel its value is 0.9 approximately and polish steel has this coefficient value of 0.07.

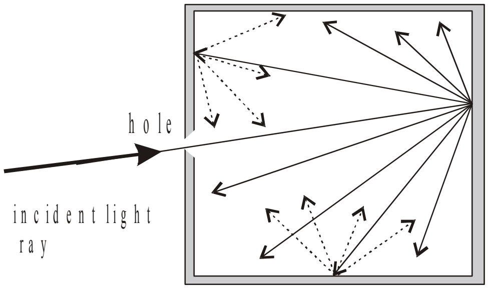

Fig.12.1

A blackbody is defined as an ideal body that absorbs all radiation incidents upon it, regardless of frequency. In the laboratory a hollow object can realize a blackbody with a very small hole leading to its interior as is shown in Fig.12.1

Any radiation striking the hole enters the cavity, where is trapped by reflection back and forth until it is absorbed.

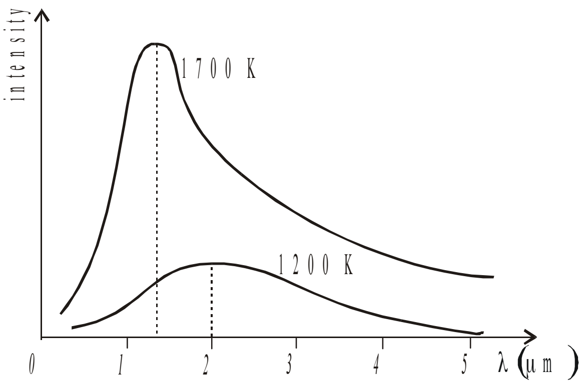

Fig.12.2

Fig.12.3

A blackbody radiates more when it is hot that when it is cold. The spectrum of hot blackbody has its peak at a higher frequency then the peak in the spectrum of a cooler one. At low temperatures, the wavelengths of the thermal radiation are mainly in the infrared region. As the temperature is increased the wavelengths shift to white region as is shown in Fig.12.2.

Graphs show power emitted by black body per unit area per unit wavelength interval (intensity) for two temperatures of the body. The total power emitted is proportional to the fourth power of the absolute temperature of the body. From this graphs we can see that the peak of the distribution shifts to shorter wavelengths with increasing temperatures. This shift was found to obey the following relationship, called *Wien's law*

$$\lambda_{\max} T = b, \tag{12.2}$$

where $b = 2.898 \times 10^{-3}$ m.K.

Study of thermal radiation shows that consists of a continuous distribution of wavelengths from the infrared, visible and ultraviolet portions of the spectrum as is shown in Fig 12.3.

The radiation of the blackbody cannot be described by the principles of classical physics. In 1900 Max Planck discovered a formula for blackbody radiation. In this theory he made two assumptions concerning the nature of the oscillating molecules of the cavity walls:

1. The oscillating molecules that emit the radiation could have only discrete energy E_n given by

$$E_n = nhf, \tag{12.3}$$

where $n = 1,2,3\ldots$ is the positive constant which is called *the quantum number*, f is the frequency of vibrations of the molecules and $h = 6.626 \times 10^{-34}$ J.s is Planck`s constant.

2. The molecules emit or absorb energy in discrete units of light energy called *quanta* or *photons*. The energy of a photon corresponding to the energy difference between two adjacent quantum states is given by

$$E = hf \tag{12.4}$$

Allowed energy levels for an oscillator of natural frequency f is shown in Fig.12.4.

From the figure we can see that *the molecules will radiate or absorb energy only when they change quantum state*.

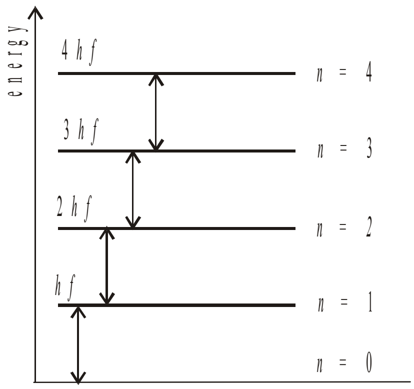

Fig.12.4

Every object radiates energy and the same time it also absorbs electromagnetic radiation. The energy that a body absorbs comes from its surroundings, which consists of other objects, which radiate energy. If an object is at a temperature T and its surroundings are at a temperature T_0, the net energy gained or lost each second by the object is given by the result of radiation as

$$P_{net} = \sigma A \varepsilon \left(T^4 - T_0^4\right) \tag{12.5}$$

where P is the energy radiated by an object per second from the area A, ε is the emissivity of the radiated object.

When an object is in equilibrium with its surroundings, it radiated and absorbs the energy at the same rate, and its temperature remains constant.

The method-practical part

A. Verification of Stefan-Bolzmann` law.

The method of the measurement of the radiation of an object is based on the measuring of the radiation of a body at the temperature T that is greater than the temperature of its surroundings T_0. The equilibrium between the radiated body and its surroundings is realized by the electric heating of the body. The power is given by

$$P = UI \qquad (12.6)$$

where U is the voltage of the source and I is applied current flowing through the body. The power equals

$$P = \varepsilon A \sigma T^4 - \varepsilon a \sigma T_0^4 + P_0 \qquad (12.7)$$

where $P_0 = k(T - T_0)$ is the power transferred from the heated body into surroundings, k is the constant of proportionality depending on the geometry of the body.

We shall use the filament of the lamp as a radiated body. Typical graph of power versus temperature is shown in Fig.12.5.

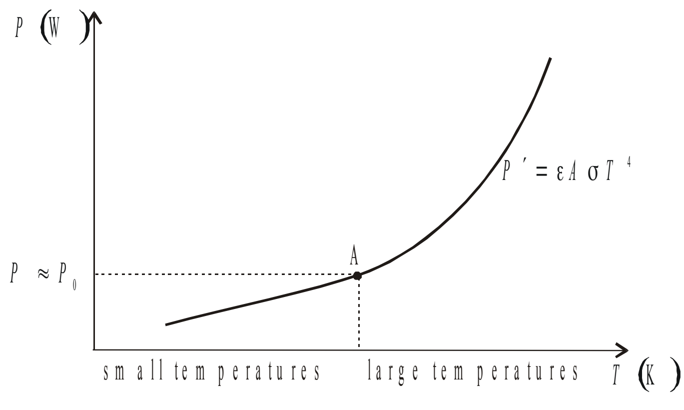

Fig.12.5

From this figure we see that the curve can be divided into two parts: linear area (low temperatures) in which the power (below the point A) depends linearly on the temperature and the area of large temperatures (above the point A). In the case of small temperatures the equation (12.7) gives

$$P \cong P_0 = k(T - T_0) \tag{12.8}$$

If the temperature of the filament is large (second part of the graph) we can neglect the second term in eq.(12.7) and we have

$$P' = P - k(T - T_0) = \varepsilon A \sigma T^4 = BT^K, \tag{12.9}$$

where $B = \varepsilon A \sigma$ is the constant for the measured filament of the lamp, $K = 4$ (it flows from Stefan-Boltzmann law). The experimental value of K will be determined by the method of measurement of the temperature dependence its resistance as

$$R = R_0(1 + \gamma \Delta T), \tag{12.10}$$

where R_0 is the resistance at room temperature T_0, R is the resistance at the temperature T (its value will be calculated from Ohm`s law as $R = \frac{U}{I}$), $\Delta T = T - T_0$ and γ is the temperature coefficient of resistivity of the material of the filament of the lamp.

Measurement

Apparatus: lamp, voltage source, voltmeter, ammeter, rheostat, computer.

Experimental procedure: Connect apparatus with respect to scheme at Fig.12.6. Measure V-A characteristic of the wolfram lamp. Since the computer controls this measurement direct by its instruction.

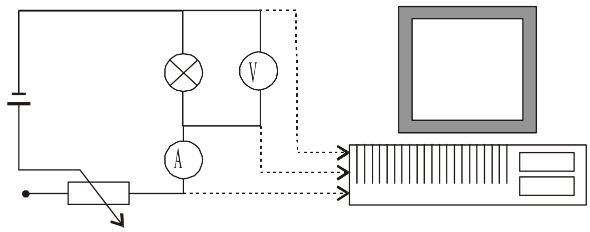

Fig.12.6

Calculation: Calculate the resistance of R_0 from first measured value. The temperature coefficient of resistivity of wolfram filament has value of $\gamma = 0.005\ \mathrm{K}^{-1}$. From the linear part of the graph $P(T)$ choose the power $P' = P - P_0$. From this equation we have

$$\ln P' = \ln B + K \ln T \qquad (12.11)$$

where $B = \varepsilon A \sigma$, K is the exponent in Stefan-Bolzmann law (see eq.(12.7)). Constants B and K are determined by the method of linear regression from the linear part of the graph of $\ln P'$ versus $\ln T$. Note that constants B and K depend on the choice of points on the linear part of the graph. Therefore, repeat this process for various values of these parameters. Present all your results and make the analysis of your measurement.

B. Determination of Stefan Bolzmann constant.

Pyrometer is an instrument used to measure the temperatures too high for ordinary thermometer. The scheme of pyrometer is shown in Fig.12.7

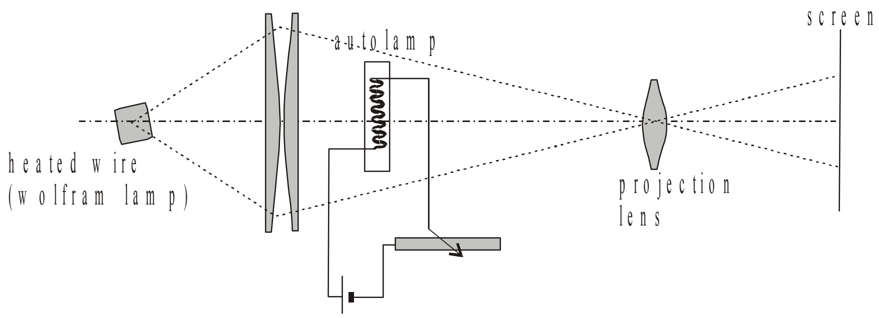

Fig.12.7

The optical pyrometer consists of the pyrometric lamp with a variable source of emf, and the optical systems. The changes of the colour of pyrometric lamp are introduced on the temperature scale of the pyrometer.

The principle of the measurement by the optical pyrometer is introduced by the showing the changes in colour and brightness that occur in an electrically heated wire (or wolfram lamp) as the current is gradually increased. This experiment shows a qualitative dependence of colour upon temperature.

At low voltage, the filament of the pyrometric lamp shows the dark against a bright background. If the voltage is increased, the filament disappears and finally reappears bright against the background of illumination. Therefore, the principle of the measurement by the optical pyrometer consists in comparison of the colour of pyrometric lamp and colour of heated filament of the lamp. If the colour of the pyrometric lamp is the same as the colour of the heated filament we read the temperature of a heated wire on the scale of the pyrometer.

Measurement

Apparatus: lamp, voltage source, voltmeter, ammeter, pyrometer.

Experimental procedure: Connect the apparatus according to scheme in Fig.12.8. Measure the room temperature T_0. The temperature of heated filament of using lamp T will be measured by the optical pyrometer for a several values of electric current I and voltage U. Record the measured values into the table.

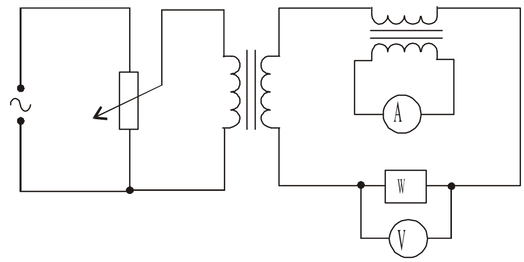

Fig.12.8

Calculation: Calculate the Stefan-Bolzmann constant for each pair of I and U from eq.(12.5). The coefficient of emissivity of the wolfram filament is approximately $\varepsilon \cong 0.6$. Give a brief discussion about the phenomena that influence accuracy of your experiment.