Student's name ____

Experiment O3

DETERMINATION OF STEFAN-BOLTZMAN CONSTANT

Objective: Study of thermal radiation. Determination of Stefan-Boltzman constant with use of pyrometer.

1 EQUIPMENT:

1) pyrometer;
2) voltmeter;
3) step-down transformer;
4) voltage regulator;
5) bulb lamp.

2 THEORY

Electromagnetic radiation of bodies at the expense of their internal energy is known as thermal radiation. Bodies radiate electromagnetic waves at arbitrary temperature but intensity and spectral composition of the radiation depends on the temperature substantially. At room temperature most of the radiation is in infrared part of the spectrum and hence is invisible.

Intensity of the thermal radiation is characterized by radiance $\boldsymbol{R_T}$. This quantity represents the energy, radiated from the unit surface area in a second. Radiance depends on a temperature, thus the thermal radiation allows body to be in thermal equilibrium with the surrounding: the more energy the body absorbs from the incident radiation, the higher its temperature rise, the more energy it emits and the equilibrium temperature is restored.

The radiant flux emitted from a unit area as waves with wavelengths in interval from $\boldsymbol{\lambda}$ to $\boldsymbol{\lambda+d\lambda}$ is known as the specific radiative intensity or spectral radiance, $\boldsymbol{r_{\lambda,T}}$. For any body the spectral radiance is proportional to its spectral absorption factor. Radiance and the specific radiative intensity are related

$$R_T = \int_0^\infty r_{\lambda,T} d\lambda . \qquad \text{(O3.1)}$$

For real bodies, the reflected radiation is superposed with the radiated one. A convenient model for thermal radiation laws study is the blackbody, which reflects none of the incident waves. All of the incident electromagnetic radiation is absorbed by the blackbody, whatever the wavelength.

J.Stefan discovered in 1879 that the radiance of a blackbody is proportional to the fourth power of the black body's absolute temperature *T*. In 1884 L. Boltzmann, using thermodynamics, derived from theoretical considerations an expression

$$R_T = \sigma T^4 , \qquad \text{(O3.2)}$$

where $\boldsymbol{\sigma}$=5,67·10^{-8} W/(K^4·m^2) is the Stefan-Boltzmann constant. The equation (O3.2) represents Stefan-Boltzmann law for blackbody radiation.

In 1900 M. Planck hypothesized that the electromagnetic waves are emitted and absorbed as discrete portions of energy (quanta), proportional to the wave frequency ν

$$\varepsilon = h\nu , \qquad \text{(O3.3)}$$

here $\boldsymbol{h}$=6,625·10^{-34} J·s is Planck constant. On basis of this hypothesis, M.Planck derived the formula for the spectral distribution of energy

$$r_{\lambda,T} = \frac{2\pi hc^2}{\lambda^5} \cdot \frac{1}{e^{hc/\lambda kT} - 1}, \qquad \text{(O3.4)}$$

here c is the speed of light, k is Boltzmann constant. Substituting (O3.4) into (O3.1) one obtains (O3.2). Formula (O3.4) is also compliant with laws experimentally discovered for thermal radiation by M. Wien:

the wavelength at which the spectral radiance $r_{\lambda,T}$ is maximal is inversely proportional to the absolute temperature (*Wien's displacement law*)

$$\lambda_{max} T = b , \tag{O3.5}$$

here b=2,9·10^{-3} m·K;

the maximal value of the spectral radiance $r_{\lambda,T}$ is proportional to the fifth power of the absolute temperature (*Wien's second law*)

$$(r_{\lambda,T})_{\max} = cT^5 , \tag{O3.6}$$

where c=1,29·10^{-5} W/(m^3·K^5).

Spectral radiance of any (non-black) body can be represented as $e_T \, r_{\lambda,T}$, where e_T is emissivity of the body. The emissivity is the ratio of the energy radiated by the given body to that of blackbody at the same temperature. Basing on equation (O3.2) for the radiance of a real body one obtains:

$$R_T = e_T \sigma T^4 . \tag{O3.7}$$

If the radiating body is placed into the medium of temperature T_0, than formula (O3.7) takes the form:

$$R_T = e_T \sigma \left(T^4 - T_0^4\right). \tag{O3.8}$$

3 DERIVATION OF COMPUTATION FORMULA AND DESCRIPTION OF EXPERIMENTAL APPARATUS

In this experiment for the determination of Stefan-Boltzmann constant the power delivered to the incandescent lamp filament is compared with the radiant flux from its surface. The glowing of tungsten filament resembles the blackbody's ones. If energy losses are neglected, the electric power spent for the filament heating up can be equated to the energy radiated by filament in a unit of time:

$$IV = A\sigma \left(T^4 - T_0^4\right), \tag{O3.9}$$

here I is current intensity, V is voltage across the lamp, A is total surface area of the filament.

From expression (O3.9) one derives the computation formula

$$\sigma = \frac{IV}{A\left(T^4 - T_0^4\right)} . \tag{O3.10}$$

Methods of temperature of distant objects determination based on the thermal radiation laws, are known as optical pyrometry. Pyrometers, used for this purpose, can be of either radiation or optical (with disappearing filament). Radiation pyrometer allows to measure temperature by total thermal radiation of the body.

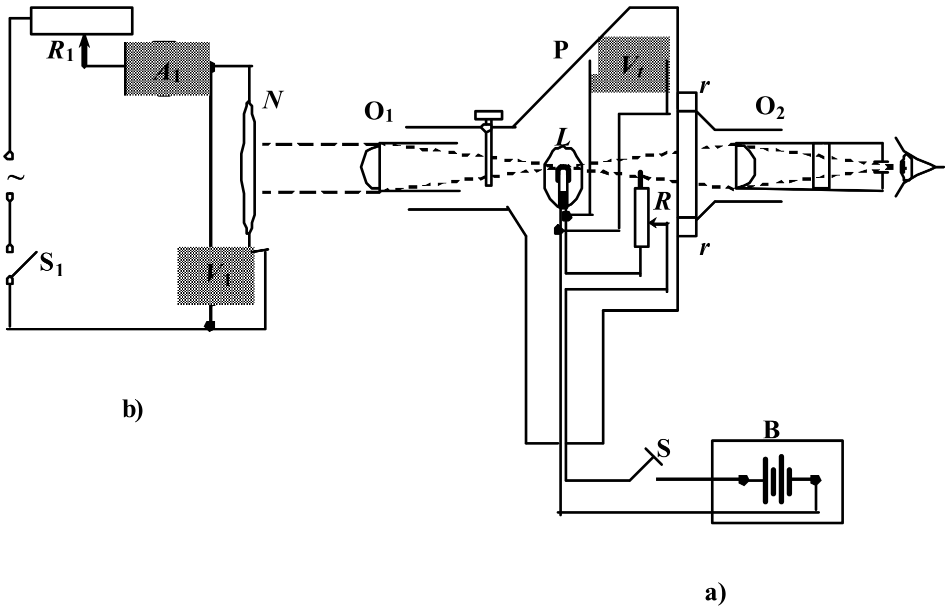

Figure O3.1

To measure the temperature of the glowing filament a radiation pyrometer can be used. Optical pyrometer with disappearing filament (fig. O3.1, a) is composed of optical system **P** with reference lamp ***L*** in the focal pint. Optical system is focused on the light source (filament of bulb lamp ***N***). Using objective lens L_1 the image of the glowing filament ***N*** is matched with the image of filament ***L***. The eyepiece L_2 produces the enlarged image of both studied and reference filaments. Reference lamp ***L*** is powered by the source **B**. The incandescence is adjusted with rheostat ***R*** by the ring ***r***, placed on frontal part of the pyrometer. The aim of ***R*** adjustment is to set the equal incandecsences of filaments ***N*** and ***L***. If this if attained, the image of reference filament ***L*** disappears against the image of filament ***N***. In this case the temperatures of both filaments are equal. Filament temperature is measured by reading of voltmeter V_t, connected in parallel to reference lamp, with the scale graduated in degrees centigrade.

4 PROCEDURE AND ANALYSIS

4.1 Check connection of elements in circuit shown in Fig. O3.1.
4.2 Slowly increasing the voltage in primary circuit by regulator, make the incandescent filament ***N*** glowing (the filament should be dark red).
4.3 Focus the objective O_1 of pyrometer of the filament ***N*** and obtain sharp image of it. Turn of the current in circuit of pyrometer lamp ***L***. Adjusting the eyepiece, obtain sharp image of the W-shape filament of pyrometer lamp ***L***.
4.4 Match images of filaments ***N*** and ***L***. Varying the current in the pyrometer lamp equalize brightnesses of filaments ***N*** and ***L***. Write down reading t_V by pyrometer scale V_t, voltmeter V_1 and galvanometer A_1 readings.
4.5 Basing on the readings t_V of pyrometer scale and positive correction determined by nomogram (Fig. O3.2) one find the actual temperature (in Celsius scale) of the incadenscent filament by formula $t_a = t_V + \Delta t$ and convert the result to Kelvin scale.

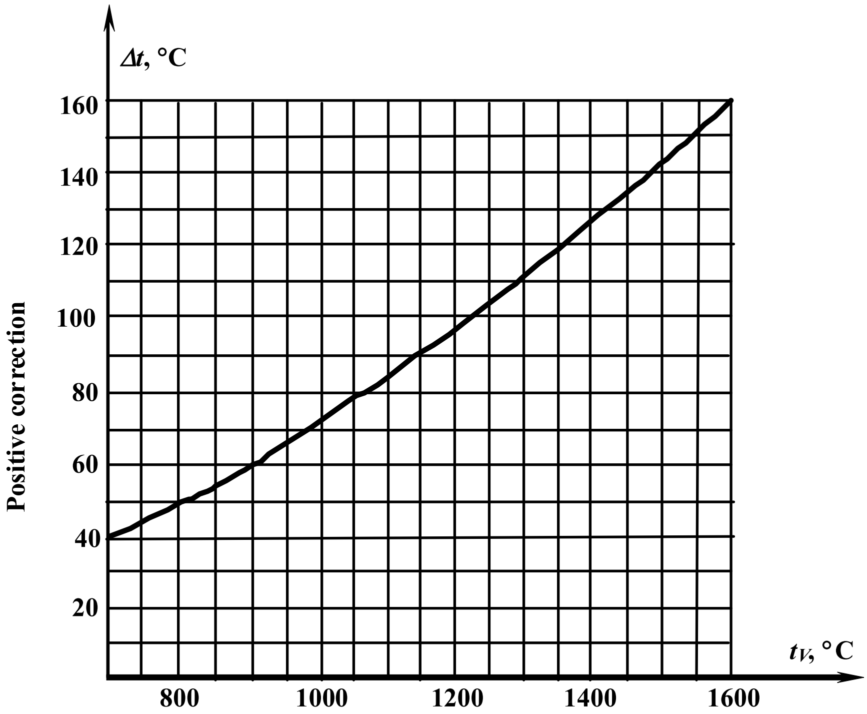

Figure O3.2

4.6 Fill the table O3.1 with the results of measurements and calculations

Table O3.1

	V, V	I, A	T_0, K	T, K	σ, $W/m^2\cdot K^4$	$\Delta\sigma$, $W/m^2\cdot K^4$	ε, %
1							
2							
3							
Mean values.							

4.7 Calculate magnitude of Stefan-Boltzmann constant by formula (O3.2).
4.8 Estimate the absolute and relative errors.
4.9 Represent the final result as

$$\sigma = (\sigma_{mean} + \Delta\sigma_{mean})\ W/(m^2K^4).$$

5 CONTROL QUESTIONS

1. What is the origin of thermal radiation?
2. What is a blackbody?
3. Formulate Stefan-Boltzman's law.
4. On the base of Wien's law, explain how radiation changes at increasing temperature?
5. Explain the principle of pyrometers operation.