Ministry of Education and Sciences of Ukraine

National University «Zaporizhzhia Polytechnic»

STUDY OF THERMAL PHENOMENA IN ELECTRICAL AND POWER ELECTRONIC APPARATUS

Methodical instructions for the lab works on the subject:
“Fundamentals of the Theory of Electrical Apparatus”

for the students of the specialty 141:
"Electrical Power Engineering, Electrical Engineering and Electromechanics "
(educational program **“Electric and Electronic Apparatus”**)

2024

Study of thermal phenomena in electric and power electronic apparatus: Methodical instructions for the lab works on the subject: “Fundamentals of the theory of electrical apparatus” for the students of the specialty 141: “Electrical Power Engineering, Electrical Engineering and Electromechanics” (educational program "Electric and Electronic Apparatus")/ Comp.: O.V. Blyzniakov. – Zaporihzhzia: NU “Zaporihzhzia Polytechnic”, 2024. – 34 p.

The compiler: Olexander BLYZNIAKOV, docent

The reviewer: Lyudmila ZHORNIAK, docent

The English text editor: Olena BONDARENKO

Responsible for the issue: Richard MOKCHNACH

Approved at the meeting of the department
"Electric and Electronic Apparatuses".
Minutes No. 8 dated January 31, 2024

Recommended for publication by
scientific-and-methodical commission
of Electrical Engineering Faculty.
Minutes No. 6 of February 22, 2024

CONTENTS

Introduction

Thermal phenomena play a very important role in electrical apparatus. Moreover, both positive and negative. An example of a positive role is the melting of a fuse link, which interrupts the electric circuit in the event of an overload or short circuit. Many other examples of the use of thermal phenomena for the operation of electrical apparatus can be given. The negative role consists mainly in that when a conductor carries current load, thermal energy is released, which must be driven out (dissipated) into the environment. Otherwise, the components of the apparatus will heat up beyond the established standards. At the same time, it should be noted that if the components of the apparatus heat up slightly under rated loads, this indicates that the design solutions are irrational. Thus, there is the task to optimize the thermal behavior of the apparatus or its individual components.

This task is especially difficult when designing *power electronic devices* (i.e. devices built on power semiconductor devices). Since the heat losses in them are much greater, in this case special *cooling systems* are needed to dissipate heat: *heat sinks*, i.e. devices with an extended cooling surface; *forced cooling*, i.e. cooling of components using a moving stream of air, water, transformer oil; *evaporative cooling*, i.e. cooling with phase change of liquid.

Thus, the apparatus or its individual element is a thermodynamic system in which thermal energy is released and, on the other hand, this is dissipated into the environment. If the released power is equal to the dissipated power, then thermal equilibrium occurs. In this case, the so-called steady thermal behavior, when its temperature does not change over time. This behavior is usually observed when the device is in long-term operation at nominal conditions. If there is no such equality (i.e., there is no thermal equilibrium), then in this case the electrical apparatus operates in an unsteady thermal conditions. In this case, the temperature of the apparatus components changes over time. This behavior is usually observed when the apparatus undergoes load fluctuations.

1. LABORATORY WORK №9: STUDY OF HEATING THE ELECTRICAL APPARATUS COMPONENTS

The duration of the laboratory study is 4 hours

1.1 Purpose the work

To have studied the temperature measuring techniques, as well as experimentally and theoretically to have determined the temperature distribution and heating time diagrams of components of electrical apparatus.

1.2 Subject of the study

As well-known experimental researches and tests of the thermal behavior of electrical and power electronic equipment, necessitate the measurement of thermal parameters, in particular, the temperature measurements. Today, there is a wide variety of temperature measuring techniques divided conventionally into contact and non-contact ones. Taking into account the relatively low cost, the main methods used today in the practice of experimental research and testing of electrical equipment remain the *contact methods*, such as thermometer, the thermocouple, and the resistance ones.

The *thermometer method* has application mainly to measure the air temperature in the room wherein thermal research or testing are performed. In some cases, this method is utilized to measure the temperature of equipment massive parts, but in the process, we must ensure its reliable thermal contact with the part.

The resistance method has found application in testing coils and for measurements in bridge circuits. As known, resistance increases linearly with temperature [1–3, 6–8], hence

$$\frac{R_1}{R_2} = \frac{R_0\left(1+\alpha\vartheta_1\right)}{R_0\left(1+\alpha\vartheta_2\right)} = \frac{1+\alpha\vartheta_1}{1+\alpha\vartheta_2},$$

where R_0 is the resistance at 0°C.

At first, R_1 is measured in the absence of current load; in the process, the temperature of the equipment element should be equal to the temperature of its surroundings. Then R_2 is measured at a certain current load after the temperature has reached its steady state value.

It should be noted that in using this method, we can determine the average winding temperature, but it is well known that the coil is heated unevenly. The highest temperature is observed within the coil body and decreases as it approaches its outer surface.

The *thermocouple method* is extensively used because it enables remote temperature measurement using an oscilloscope or digital recording system with visualization on PC. The following types of thermocouples are mainly used: Copper-Constantan, Chromel-Copel, Chromel-Alumel. At relatively low temperatures (up to 100...120°C), it can be assumed that the thermo-EMF is proportional to the temperature difference between the hot and cold junctions of the thermocouple. Taking into account that the input impedances of the recording device $r_п$ and the thermocouple $r_т$ are comparable, the device will record the value smaller than the thermo-EMF:

$$e_п = e_т \frac{r_п}{r_т + r_п} = \frac{\alpha \cdot r_п}{r_т + r_п} \tau .$$

To ensure a minimum error, the following conditions must be fulfilled:

a) the thermocouple must be securely pressed to the part to be tested; if there is an opportunity, it should be soldered, welded or punched into the surface; in some cases, the thermocouple is soldered to a copper plate, which is pressed to the surface under test;

b) in order to avoid generating induced EMF, the conductors connecting the thermocouple to the recording device must be twisted into bifilar and placed as far away from the area of magnetic field action as possible;

c) to derive accurate measurements, it is desirable to utilize compensatory measurement methods, or devices with a high input resistance graduated in compliance with the experiment conditions.

Contactless methods have recently gained intensive development. This is, firstly, the use of *pyrometers* based on analyzing the physical characteristics of electromagnetic radiation generated by heated bodies; and, secondly, the use of *laser thermometry methods*. Their main advantage is the absence of a thermosensitive element, that is, a temperature sensor; the research object itself plays this role.

Non-contact methods, in particular spectral pyrometers, have found application in the practice of testing electrical equipment. The presence of certain equipment defects causes a change in the temperature of the defective elements occurred with a change in the intensity of infrared radiation. The use of technical means of thermal imaging diagnostics (thermal imaging cameras) enables us to obtain a visual image of the temperature field on the surface of the object and immediately identify the defective element. A significant disadvantage of pyrometers is relatively high errors; in addition, they react to thermal interference from external heat sources.

1.3 Description of the lab setup

In performing the lab work, temperature-rise is measured by the thermocouple method. Thermocouples are located uniformly along the radius and axis of the winding cross-section, as shown in Figure 1.1, which enables us to study the temperature distribution within the winding body.

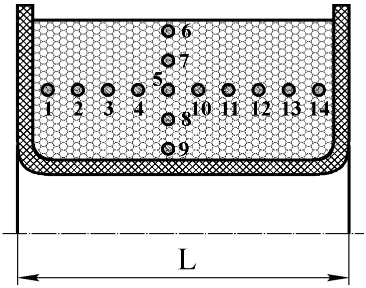

Figure 1.1 – Arrangement of thermo-couples in the winding cross-section

The circuit diagram of the lab setup is given in Figure. 1.2. The circuit is powered with the circuit breaker SF. All thermocouples located in the coil are connected to multi-position switch S1. The thermo-EMF is measured with a millivoltmeter PV. The required value of the current in the coil or rheostat is set using the autotransformer T. Two-position switch S2 applies supply to the coil (position 1) or the rheostat (position 2).

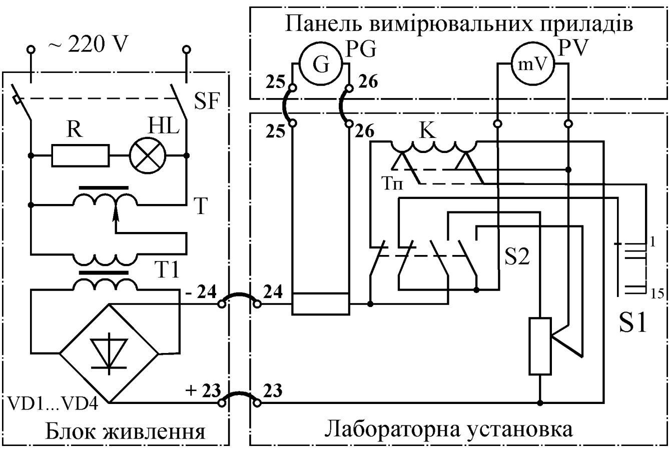

Figure 1.2 – Circuit diagram of the lab setup

1.4 Tasks

1.4.1 Measure time diagrams of temperature-rises for the coil points located on the outer and inner surfaces, at central part of the cross-section, as well as for the point touching the magnet core.

1.4.2 Determine the steady state temperature-rise on the surface of the coil, as well as its heating time constant using the part of the experimental heating curve.

1.4.3 In the steady state conditions, determine the temperature-rise distribution along the radius of the coil and along its axis, as well as the average temperature-rise of the coil.

1.4.4 Using experimental findings, calculate the heat transfer coefficients from the inner and outer surfaces and the coil thermal conductivity.

1.4.5 Measure time diagrams of the temperature-rise of the air-cooled rheostat in long-term and intermittent cycle duties of operation.

1.4.6 Determine the main values that characterize the rheostat heating process.

1.4.7. Determine the overload factor for the air-cooled rheostat for intermittent cycle duty of operation.

1.5 Methodical instructions

1.5.1. The experimental part of the work concerning heating the winding is carried out in the following order:

a) connect the lab panel to the power source (connect terminals 23-23 and 24-24 with short conductors);

b) set the switch S1 to position 1 and make the circuit breaker SF;

c) using autotransformer T, set a current of 4 A and keep it invariable during the experiment;

d) readings of thermocouples 5–9 should be counted every 5 minutes and listed in the table 1.1 until the temperature reaches its steady state value.

Table 1.1 – Measuring and calculated findings

Time	Experimental findings	Numbers of thermocouples				
		5	6	7	8	9
5 minutes	U, mV					
	ϑ, °C					
10 minutes	U, мВ					
	ϑ, °C					
. . .						
130 minutes	U, мВ					
	ϑ, °C					

e) when the temperature of the coil reaches its steady state value, enter the readings of all 14 thermocouples into table 1.2.

Table 1.2 – Experimental findings of steady state conditions of the coil

Values	Numbers of thermocouples													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U, мВ														
ϑ, °C														

f) break circuit breaker SF and bring the autotransformer out to zero.

1.5.2. The experimental part of the work concerning heating the rheostat is carried out in the following order:

a) set the S1 switch to position 2 and make circuit breaker SF;

b) using the autotransformer T, set a current of 2.5 A and keep it invariable during the experiment;

c) readings of thermocouples should be counted every 3 minutes and listed in the table 1.3 until the temperature reach its steady state value.

Table 1.3 – Experimental findings of heating the rheostat

Time in minutes	0	3	. . .	130
U, mV				
ϑ, °C				

d) when the temperature of the rheostat reaches its steady state value, change over it to intermittent cycle duty with a no-load duration of 8 minutes and an on-load duration of 6 minutes;

e) operation in this duty is continued until a quasi-steady state conditions; enter the data into the table. 1.3.

f) break circuit breaker SF and bring the autotransformer out to zero.

1.5.3. The processing of the experimental findings, in particular the determining temperatures based on the measured thermo-EMF, should be carried out according to the procedure represented in Annex B.

1.5.4. The average temperature-rise of the coil is determined by the following formula:

$$\tau_{\text{av}} = \frac{\tau_{\max} + \tau_2}{2},$$

where τ_{max} is the maximum temperature-rise increase in the coil;

τ_1 – temperature-rise of the coil outer surface (according to the readings of thermocouple 6).

1.5.5. The heating time constant is determined graphically based on the heating curve as shown in Figure 1.3a. The time constant can also be determined as the time at which the temperature-rise is approximately two-thirds of its steady state value.

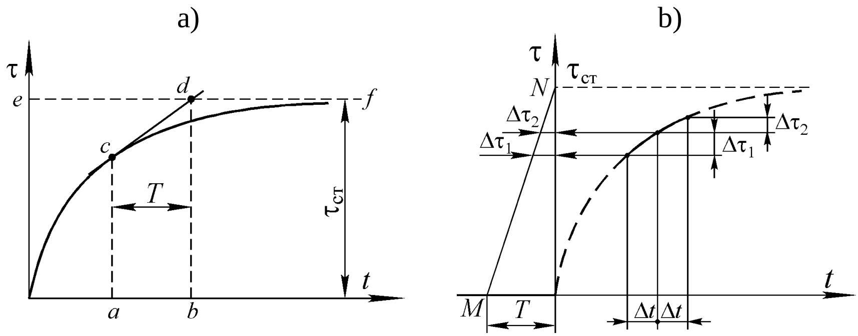

Figure 1.3 – Graphical determination of heating time constant (a) and steady state temperature-rise (b)

1.5.6. Steady state temperature-rise can also be determined graphically. In the process, only a part of the heating curve $\tau_{av}(t)$ (at the section where it sharply bends) can be used, as shown in Figure 1.3b.

Steady state temperature-rise can also be determined by the empirical formula [6–8]:

$$\tau_{\text{ст}} = \frac{\tau_2^2 - \tau_1 \cdot \tau_3}{2\tau_2 - \tau_1 - \tau_3},$$

where τ_1, τ_2, τ_3 are the temperature-rises measured at time intervals Δt (see Figure 1.3b).

1.5.7. The values of heat transfer coefficients from the inner and outer surfaces of the coil are determined by the following formulas, respectively:

$$\alpha_{\text{т}1} = \frac{P_1}{2\pi r_1 l(\vartheta_1 - \vartheta_0)}; \quad \alpha_{\text{т}2} = \frac{P_2}{2\pi r_2 l(\vartheta_2 - \vartheta_0)},$$

where P_1 and P_2 are the power driven out from the inner and outer cylindrical surfaces of the coil, respectively;

ϑ_1 and ϑ_2 are the temperatures on the inner and outer surface of the coil, respectively;

For the coil with a heat-insulated end, the powers can be determined by the following equations:

$$P_1 = P_0 \frac{r_0^2 - r_1^2}{r_2^2 - r_1^2}; \qquad P_2 = P_0 \frac{r_2^2 - r_0^2}{r_2^2 - r_1^2},$$

where P_0 is the power consumed by the coil in steady state conditions, W;

r_0 is the radius corresponding to the maximum temperature in the coil.

1.5.8. Heating curves should be plotted for the outer and inner surfaces of the coil, as well as the central part its cross-sectional area (thermocouples 6, 7, 5, 8, 9; see Figure 1.1).

1.5.9. Plot the distribution curve of winding temperature-rise in the radial and axial directions. Determine the radius corresponding to the maximum temperature-rise.

1.5.10. Based on the obtained values of steady state temperature and heating time constant, on the same graph, plot the calculated (dashed) heating curve and compare it with the experimental results.

1.5.11. The laboratory work report should contain:

a) tasks and initial data for calculation;

b) circuit diagram of the study;

c) graphs of dependencies to be studied;

d) calculations and computation formulas;

e) analysis of the obtained dependencies;

1.6 Self-checking questions

1.6.1. The main thermal sources in electrical apparatus.

1.6.2. Basic temperature measuring techniques of electrical apparatus components.

1.6.3. The physical meaning of the heat transfer coefficient from the surface of a heated body.

1.6.4. The definition and physical meaning of the heating time constant.

1.6.5. The notion of steady state temperature.

1.6.6. The main operational duties of electrical apparatus.

1.6.7. Heat transfer in direct and alternating current windings with available magnet core.

1.6.8. What is the thermal conductivity of a winding equivalent body?

1.6.9. In what case is the most heated layer in the coil located on its inner surface?

1.6.10. Give the definition of the overload factor in terms of power and current in the short-term and intermittent cycle duties.

1.6.11. What is the relative duty of the intermittent operation of the device?

2. LABORATORY WORK № 13. STUDY OF HEAT SINKS FOR POWER SEMICONDUCTOR DEVICES

The duration of the laboratory study is 4 hours

2.1 Purpose of the work

The purpose of the lab work is to determine experimentally the efficacy of using heat sinks to ensure the optimal thermal behavior of power semiconductor devices.

2.2 Subject of the study

The normal functioning, and hence the loading capability, of a power semiconductor device (PSCD) depends entirely on its *p-n* junction operating temperature, for which rather strict frameworks have been established. Permissible temperature values of the *p-n* junction are usually provided in the passport data of the devices and in no case can they be exceeded during their operation. It is known that PSCD, in particular its *p-n* junction, is a concentrated thermal source. In this situation, the task to dissipate (drive out) a large amount of thermal energy to the environment is quite difficult. It is solved mainly by using various coolers or cooling systems [10].

In the general case, the thermal state of the PSCD can be determined using the equivalent thermal circuit, which is given in Figure 2.1.

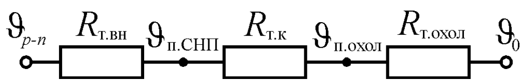

Figure 2.1 – Equivalent thermal circuit of PSCD with one-sided cooling

There are following notations used in the equivalent circuit:

$\vartheta_{p\text{-}n}$ is the *p-n* junction temperature of the PSCD;

$\vartheta_{c.PSCD}$ and $\vartheta_{c.c}$ are the contacting surface temperature of the PSCD and the cooler, respectively;

ϑ_0 is the ambient temperature;

$R_{th.in}$ is the internal thermal resistance of the PSCD (between its *p-n* junction and the surface in contact with the cooler);

$R_{th.con}$ is the contact thermal resistance (between the contact surfaces of the PSCD and the cooler);

$R_{th.c}$ is the thermal resistance of the cooler (between its contact surface and the surrounding environment).

According to the equivalent circuit, the thermal power driven out by the cooler to the environment will be evaluated by the following expression:

$$P_{\mathrm{out}} = \frac{\vartheta_{\mathrm{c.c}} + \vartheta_0}{R_{\mathrm{th.c}}}. \tag{2.1}$$

Hence, in order to provide high values of the heat flow at the same temperature-rise, it is necessary to reduce the thermal resistance of the cooler, which in general can be evaluated by the following formula:

$$R_{\mathrm{th.c}} = \frac{1}{\alpha_{\mathrm{th}} S_{\mathrm{cool}}}. \tag{2.2}$$

where S_{cool} is the area of the surface to be cooled;

α_{th} is the heat transfer coefficient;

In such a way, the thermal resistance of the cooler can be reduced by the increase in the heat transfer coefficient or extend of the surface of heat transfer.

The heat transfer coefficient can be increased in the following ways. First, it is the utilization of an effective coolant medium (for example, liquid instead of air), as well as increasing the speed of its circulation (that is, the use of forced convection and create turbulence of the cooling medium flow). In the process, it should be noted that these measures require to install additional devices (pump, fan, pipelines, valves, expansion tank, etc.), which often leads to a significant increase in weight-and-size performances, complication of the equipment design, as well as a significant increase in capacity consumed to move the refrigerant in the system. Secondly, it is the use of *evaporative cooling* (that is, driving out thermal energy in changing the coolant aggregate state), which enables significantly increase the heat transfer coefficient compared to liquid (including forced) cooling. It should be noted that the efficacy from the use of evaporative systems for cooling PSCD has not yet been proven [10].

Thus, reducing the thermal resistance of the cooler only by increasing the heat transfer coefficient is not always appropriate. An effective technique to achieve of the denoted goal is the utilization of expanded heat exchange surface by the way of finning (the use of ribs or pins). Devices or parts with an expanded (finned) surface are usually called *heat sinks*.

Of course, an extend of the heat exchange surface does not lead to a proportional increase in the heat exchange properties of the heat sink because of the uneven distribution of temperature along the height of the fin. An experience shows that the maximum temperature is observed at the fin basement, that is, the heat sink surface where the fins are located. Therefore, to evaluate the efficacy of the use of expanded (ribbed) surfaces, in the practice of calculating and designing heat sinks, the concept of *efficiency of the fin* or *finning* is often used. It is usually defined as the ratio of thermal energy dissipated by the finned surface to the so-called *ideal energy*. The ideal energy in this case is defined as the energy dissipated by the finned surface under the condition of uniform distribution of the basement temperature over the entire surface of the fins. The efficiency of the fin is determined by the following formula [6]:

$$\eta = \frac{\operatorname{th} bl}{bl}, \tag{2.3}$$

where l is the height of the fin;

b is a fin parameter determined by the following formula:

$$b = \sqrt{\frac{\alpha_{\text{th}} p}{\lambda S}}, \tag{2.4}$$

where α_{th} is the heat transfer coefficient from the fin surface, W/(m^2·K);

S, p are the cross-sectional area of the heat sink fin in the direction of heat transfer and its perimeter, respectively, m^2, m;

λ is thermal conductivity of the heat sink material, W/(m·K).

The main parameter that characterizes the heat exchange properties of the heat sink is its thermal resistance or thermal conductivity. The expression for the thermal resistance of a rectangular cross-section fin of width h, which is much greater than its thickness δ (i.e. $h >> \delta$), has the following form:

$$R_{\text{th}\Sigma} = \frac{1}{h\sqrt{2\delta\lambda\alpha_{\text{th}}} \cdot \operatorname{th}\left(l\sqrt{\frac{2\alpha_{\text{th}}}{\lambda\delta}}\right)}, \tag{2.5}$$

Thus, the aggregate thermal conductivity of the heat sink under such conditions will be determined by the following expression:

$$G_{\text{th}\Sigma} = G_{\text{th.nf}} + Nh\sqrt{2\delta\lambda\alpha_{\text{th}}} \cdot \text{th}\left(l\sqrt{\frac{2\alpha_{\text{th}}}{\lambda\delta}}\right), \tag{2.6}$$

where $G_{\text{th.nf}}$ is the thermal conductivity of the heat sink part, where there are no fins; if this part does not dissipate heat, this conductivity component should not be taken into account;

N is the number of heat sink fins.

There are following parameters also used to characterize the heat exchange properties of the heat sink:

$\alpha_{\text{th.ef}}$ is the effective heat transfer coefficient, which is determined under the condition of substitution of the real finned surface with a smooth surface, which is equal to the area of the heat sink basement; the $\alpha_{\text{th.ef}}$ value can be used to estimate the efficacy of heat sinks to be developed or selected for cooling PSCD.

ϑ_{av} is the average surface temperature of the heat sink basement, °C;

A is the area of the heat sink basement, where the fins are located, m^2;

Φ is the heat flux being dissipated, W.

The relationship between the parameters of the heat sink is determined by the following expressions:

$$G_{\text{th}\Sigma} = R_{\text{th}\Sigma}^{-1} = \alpha_{\text{th.ef}}A; \tag{2.7}$$

$$\Phi = G_{\text{th}\Sigma}(\vartheta_{\text{s}} - \vartheta_0) = \frac{\vartheta_{\text{s}} - \vartheta_0}{R_{\text{th}\Sigma}} = \alpha_{\text{th.ef}}A(\vartheta_{\text{s}} - \vartheta_0). \tag{2.8}$$

If the fins are located on a rectangular basement with sides L_1 and L_2, then:

$$A = L_1 \cdot L_2 .$$

If the fins are located on the cylindrical surface with diameter D and length L, then:

$$A = \pi DL .$$

If the fins are located on a round basement with a diameter of D, then:

$$A = \frac{\pi D^2}{4} .$$

2.3 Description of the lab setup

Three heat sinks with rectangular fins are studied in the laboratory work. A heater, simulating power semiconductor device, is installed on each one. The appearance of heat sinks with heaters is given in Figure 2.2, which also shows the points for temperature measurements: 1 – the outer surface of the heater; 2 and 3 – contact surfaces of the heater and heat sink, respectively; 4 – heat sink basements.

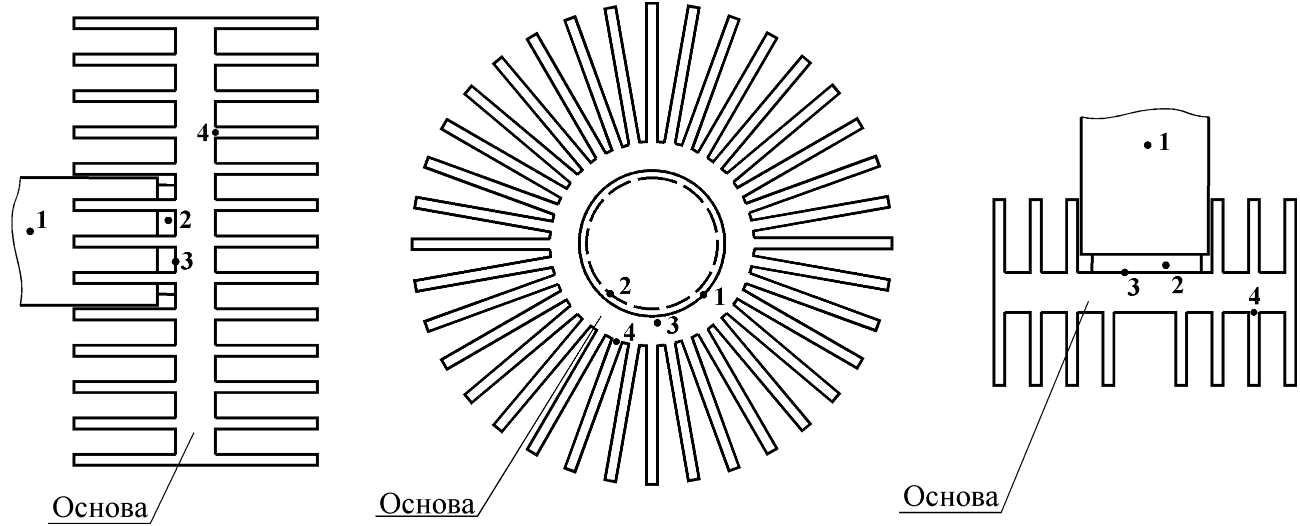

Figure 2.2 – Appearance of the test heat sinks (the point for temperature measurements are designated by numbers 1–4)

The circuit diagram of the setup is shown in Figure 2.3. The installation enables to adjust the loss power in each heater U1, U2 and U3. Heaters are supplied via three-position switches S1–S3. In the "Control" position, using the autotransformer T, the predetermined power of the corresponding heater is adjusted according to the readings of the ammeter PA2 and the voltmeter PV1. A more accurate adjustment of the heater to the predetermined power is carried out with the help of resistors R1–R3. The switch is then set to the neutral position, which corresponds to the off position of the corresponding heater. Similar operations are carried out with other heaters.

WARNING! Only one switch must be in the "Control" position, since the measurement limits of the PA2 ammeter are designed for the load of only one heater.

The study of thermal behavior of heat sinks, according to the task, is carried out in the working position of the heaters. To do this, switches S1–S3 are set to the "Start" position in any combination. In the process, the PA1 ammeter shows the total current of all the supplied heaters and enables to visually control the stability of the current load.

To measure the temperature of the heat sinks and heaters, the contact method is used; the temperature sensor is pressed to the point under study. As a temperature sensor, a semiconductor thermistor LM35 is used, which has the form of a temperature probe, connected to a digital voltmeter. The connection diagram of the thermistor is provided in Annex B.

2.4 Tasks

2.4.1 Study the main types of cooling systems and types of coolers used for power semiconductor devices.

2.4.2 Experimentally determine the heating curve and time constant of the heater-heat sink units arranged on the laboratory setup.

2.4.3 Experimentally determine the temperature distribution of the heater-heat sink blocks arranged on the laboratory setup in steady state and plot its graph.

2.4.4 On the basis of experimental findings and by calculation, determine the main parameters of the heat sinks arranged on the laboratory setup: thermal resistance, effective heat transfer coefficient and efficiency of finning.

2.4.5 Compare the experimental and calculation findings.

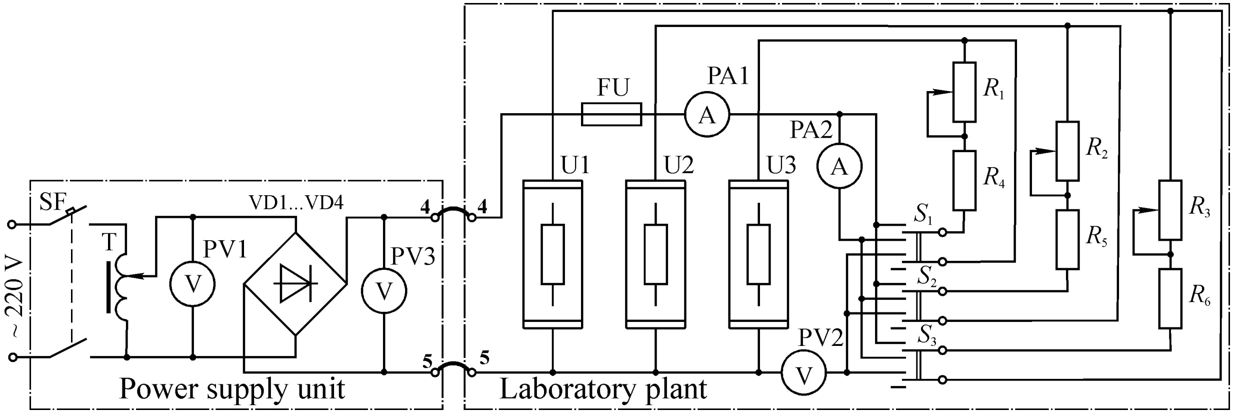

Figure 2.3 – Circuit diagram of the lab setup

2.5 Methodical instructions

2.5.1 In order to perform points 2.4.1, it is necessary, first, to study the theoretical material and pay attention to the main factors affecting the operability of the system “device-cooler”. In the process, one should not be considered only natural air cooling systems, but also pay attention to more effective cooling systems for PSCD [10].

2.5.2 To perform theoretical calculations, it is necessary to use the relationships given in subsection 2.2 [9, 10]. The heat transfer coefficient is determined by the formulas given in Annex B. All the necessary geometric dimensions of heat sinks and heaters are determined by measuring directly on the lab setup. The heat sinks arranged on the lab stand are made of AD-31 aluminum alloy with thermal conductivity $\lambda = 200\ \text{W}/(\text{m} \cdot \text{K})$.

2.5.3 The experimental part of the work is performed in the following order:

a) prepare the temperature sensor for work; to do this, it is necessary to turn on the digital voltmeter and set the measurement range to 2 V (2000 mV);

b) make the automatic switch SF and, using the autotransformer T, adjust the voltage specified by the teacher (according to the readings of the PV1 voltmeter)

c) energize one of the heaters; to do this, it is necessary to set the corresponding switch S1, S2 or S3 to the "Control" position; at the same time, other heaters must be de-energized;

d) with the help of resistor R1, R2 or R3, set the specified power on the energized heater (according to the readings of the ammeter RA2) and de-energize it;

e) carry out similar operations with other heaters;

f) at the instruction of the teacher, set the switches S1–S3 to the «Раб» position, fixing the start of heating of the studied blocks with the help of a timer;

g) using a probe with a temperature sensor, measure a heating curves of the points 1–4 of the heater–heat sink block, indicated in Figure 2.2; enter the data in table 2.1 (the heating process can be considered as steady state if consecutive measurements after 5 minutes differ by no more than 1°C);

WARNING! To obtain accurate measurements, the temperature prod should be held at the tested point until a stable temperature reading is obtained (approximately 25–30 s)

g) when steady state condition is reached, measure the temperature distribution of the heat sink according to teacher instruction; enter the findings into the table 2.1;

Table 2.1 – Experimental heating curve for heater–heat sink unit, °C

Time in minutes	The temperatures of heater–heat sink unit			
	Point 1	Point 2	Point 3	Point 4
5				
10				
15				
…				

h) the experimental value of the average surface temperature is defined as the arithmetic meanvalue of several temperatures measured at different points of the basement of the heat sink;

i) the experimental value of the thermal resistance of the heat sinks is determined by formula (2.1), in which the thermal power dissipated by the heat sink P_{dis} is the heat flow passing through its contact surface with the heater; it is defined as the difference:

$$P_{\text{dis}} = P_{\text{rel}} - P_{\text{dis.c}},$$

where P_{rel} is the thermal power released by the heater;

$P_{dis.c}$ is the thermal power dissipated by the heater directly through its surface that has not contact with the heat sink; according to Newton's law of cooling, it can be determined by the following formula:

$$P_{\text{dis.c}} = \alpha_{\text{th.heat}} S_{\text{heat.nc}} (\vartheta_{\text{heat}} - \vartheta_0),$$

where $\alpha_{th.heat}$ is the total heat transfer coefficient from the heater surface that has not contact with the heat sink;

$S_{heat.nc}$ is the area of the heater surface that has not contact with the heat sink;

ϑ_{heat} is the temperature on the heater surface; the experimental value of steady state temperature at point 1 should be used in calculation process.

2.5.6 The lab work report should contain:

a) name and purpose of work;

b) sketches of the units with the required dimensions;

c) calculations of heater capacities;

d) tables of experimental dependencies and corresponding graphs;

e) comparative analysis of theoretical and experimental values of the main performances of heat sinks according to the task.

f) conclusions from the work.

2.6 Self-checking questions

2.6.1 What factors affect the heat transfer capability of the heat sink?

2.6.2 What techniques enable to reduce the contact thermal resistance the between the device and the cooler?

2.6.3 What is the efficacy of the fin and what does it depend on?

2.6.4 What does the thermal resistance of the cooler depend on?

2.6.5 How does the color of the heat sink affect its heat transfer capability?

2.6.6 How to choose a heat sink for natural air-cooling?

2.6.7 Why is the effective heat transfer coefficient a criterion for evaluating the efficiency of a heat sink?

2.6.8 What types of heat sink designs are used for natural cooling of semiconductor devices?

2.6.9 How does the power released in the device and dissipated by the heat sink affect the temperature of the device casing?

3. LABORATORY WORK №14.
STUDY OF THERMAL BEHAVIOR OF INHOMOGENEOUS CURRENT CARRYING SYSTEM

Duration of scheduled laboratory study is 4 hours

3.1 Purpose of the work

The one is to master the theoretical and experimental methods of researching the thermal state of current-carrying systems of electrical apparatus in different operating conditions.

3.2 Subject of the study

Regardless of the specific purpose, one of the functions of electrical apparatus is electric current carrying at the nominal conditions (long-term, short-term, intermittent cycle). When the current carrying system of the apparatus operates in nominal conditions, its components, as well as adjacent members undergo heating. Under the influence of electromagnetic fields, currents can also flow in non-conductive components of the device, also causing their heating.

It is known that the heating temperatures of current-carrying systems of electrical apparatus are limited by valid standards and technical specifications [11, 12]. Therefore, determining the heating temperatures of current- carrying systems and, in general, the thermal behavior of the apparatus is a very important task that is solved during their development and modernization.

When the load current flows for a long time, the current-carrying systems of real devices frequently have a non-uniform temperature field due to the non-uniformity of structural and thermal-and-physical factors. For example, the current-carrying system of switching devices, at least, contains several conductors distinctive by geometric configuration, material and heat transfer conditions; in addition, they contain switching contacts and contact connections. Contactless switching devices additionally contain power semiconductor devices with coolers.

It should be noted that the thermal calculations of even simple, structurally uniform current-carrying systems of devices are quite complex, which does not allow to determine with satisfactory accuracy at the design stage the temperature of individual elements and the thermal behavior of the device in general, taking into account all factors. Therefore, the experimental determination of the thermal behavior is the most objective and accurate.

3.3 Description of the lab setup

Six variants of current-carrying conductors are installed on the setup for experimental research that is shown in Figure 3.1.

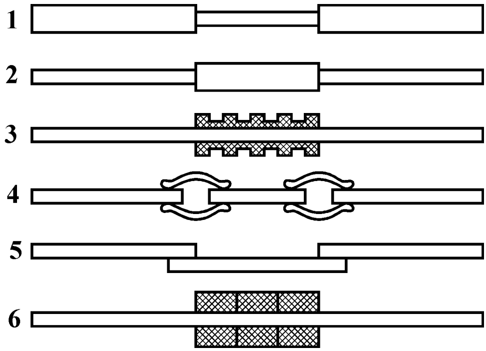

Figure 3.1 – Variants of current-carrying conductors

For temperature measurements in the conductors, as in the previous laboratory work, a temperature sensor LM35 connected to a digital voltmeter is used (see annex B).

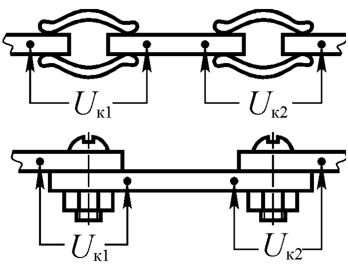

Figure 3.2 – Scheme for contact voltage drop measurement

The voltage drop across the contacts of the conductors is measured by a digital voltmeter. Any DC voltmeter with a high internal impedance (at least 100 kΩ) can be used for this purpose. The device terminals must be connected to wires with probes at their ends. The probes during measurement should install at the points near the contact as shown in Figure 3.2.

Heating the conductors are carried out by DC current, the circuit diagram of their connection is given in Figure 3.3. From one to six series-connected conductors can be under load R_{load}.

WARNING! If the calculated current load of the conductors is different, then their research must be performed separately. The connection of current conductors to the testing circuit is carried out by means of a bolted connection.

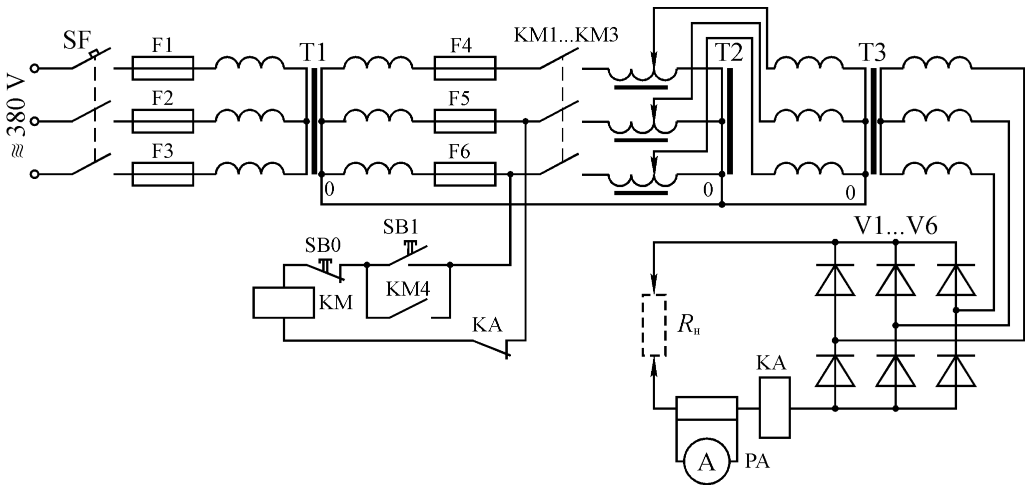

Figure 3.3 – Electrical connection circuit of the conductors

The lab setup is energized by the automatic circuit breaker SF (common to the whole lab) and the magnetic starter KM by pressing the push button SB1 (Start).

The load current is adjusted using autotransformer T2; its value is determined by the readings of ammeter PA. When the current increases to more than 100 A, the current relay KA actuates, and its normally closed contact de-energizes the coil of the magnetic starter KM.

3.4 Tasks

3.4.1 Determine the permissible current load of the conductor (the option is determined according to the instruction of the teacher).

3.4.2 Perform a confirmative analysis of the conductor being researched at steady state condition.

3.4.3 Experimentally determine the heating time constant of the conductor and the time of its putting into a steady state; plot a heating curve for the conductor.

3.4.4 Experimentally determine the temperature distribution along the length of the conductor, as well as the temperatures at its ends and the power loss at the contact connections in a steady state.

3.4.5 Conduct a comparative analysis of the findings of theoretical and experimental research.

3.5 Methodical instructions

3.5.1 In order to determine the permissible current load of the conductor, it is necessary to draw up thermal equivalent circuit and use Ohm's or Newton's laws, as well as simplified dependencies to determine the heat transfer coefficients [2, 3, 6–9].

3.5.2 The results of the preliminary calculation (allowable current load) must be agreed with the teacher and, accordingly, permission to conduct the experimental part of the work must be obtained.

3.5.3 The experimental part of the lab work should be performed in the following order:

a) construct the circuit, prepare the conductor according to the given option;

b) prepare the temperature sensor for work; to do this, it is necessary to turn on the digital voltmeter and set the measurement range to 2 V (2000 mV);

c) make the automatic breaker SF and by pressing the push button SB1 (Start), make the magnetic starter KM;

d) using autotransformer T2, adjust the permissible load current found by the calculation (item 3.5.1);

e) to perform the task 3.4.3, it is necessary to measure the temperature at 3–4 points of the conductor at equal intervals (determine yourself); to derive accurate measurements, the probe should be held at the point until a stable temperature value is obtained, that is, approximately 25– 30 s; enter the findings into the table (construct yourself);

e) the heating process is considered as steady state if during 5 minutes the temperature values in each of the points do not differ by more than 1°C;

g) when a steady state has reached, measure the temperature throughout the length of the conductor; determine the number of measurement points himself taking into account the need to construct a temperature distribution graph;

h) record the temperature values at the ends of the conductor and the voltage drop at the contact connections.

3.5.4 To measure directly the surface temperature of the conductor on a section where it is covered with an insulation layer is impossible; therefore, the insulation surface temperature is measured, and the temperature of the conductor surface at this section is calculated using the following formula:

$$\vartheta_{\text{s.c}} = \vartheta_{\text{s.ins}} + r_{\text{th.ins}} \cdot q,$$

where $\vartheta_{\text{s.ins}}$ is the temperature at the research point on the surface of the insulation, which is determined experimentally;

$r_{\text{th.in}}$ is thermal resistance of the insulation layer per its unit length at the section of the temperature measurement, (m·K)/W;

q is the power losses in the conductor per its unit length at the section of temperature measurement, W/m.

The last two parameters are determined by the calculation method.

3.5.5 The refined calculation of the conductor in the steady state is performed in the following order [2, 3, 13]:

a) determine sections of the conductor, which, in terms of thermal behavior, can be described by differential equations;

b) construct a thermal equivalent circuit of the conductor;

c) construct a block diagram and an algorithm for the refined calculation of the conductor taking into account the nonlinearity of the parameters of heat generation and heat transfer (using the method of successive approximations), focusing on the following approximate sequence:

- determine the expression for calculating heat transfer parameters;

- set up a system of differential equations;
- determine boundary conditions and conditions of temperature field continuity at the boundaries of the sections;
- determine the method for solution of the system of equations;
- present a computational algorithm of the temperature distribution along the conductor.

d) calculate the temperature distribution along the length of the conductor according to the initial data.

3.5.7 The lab work report should contain:

a) name and purpose of work;

b) a sketch of the conductor under study;

c) calculation of permissible current load;

d) results of experimental and theoretical research in the form of tables and graphs;

e) analysis of conducted research and conclusions from the work.

3.6 Self-checking questions

3.6.1 What is the purpose of the preliminary (check) thermal calculation of the conductor?

3.6.2 What is the heating time constant of the conductor?

3.6.3 How is the putting time of the conductor into a steady state heating duty determined?

3.6.4 How does the presence of an insulation layer affect the heat transfer capability of the conductor?

3.6.5 Name the main stages of the confirmative thermal calculation of the conductor.

3.6.6 How is the temperature of the conductor section covered with an insulation layer determined?

3.6.7 How do connecting wires affect the thermal behavior of the conductor?

Reference List

1. Козлов В.Д. Електричні апарати. Загальні питання електричних апаратів: Посібник [Електронний ресурс] – К.: НАУ, 2005. – 92 с.

2. Рассальський О.М. Аналіз і розрахунок теплових режимів силового електроустаткування: Навчальний посібник / О.М. Рассальський. – Запоріжжя: ЗНТУ, 2005. – 146 с.

3. Близняков О. В. Thermal Behavior Analysis of Power Electric and Electronic Equipment = Аналіз теплових режимів силового електричного та електронного обладнання: Навчальний посібник. – Запоріжжя : ЗНТУ, 2014. – 146 с.

4. Heat transfer handbook / Edited by Adrian Bejan and Allan D. Kraus, John Wiley & Sons, Inc., 2003. – 1481 p.

5. Nellis, G. Heat transfer / Edited by Gregory Nellis, Sanford Klein, Cambridge University Press, 2009. – 1143 p.

6. Основы теории электрических аппаратов: Учеб. для вузов [Електронний ресурс] / Под ред. П.А. Курбатова – СПб.: Лань, 2015. – 590 с.

7. Теория электрических аппаратов/ [Г.Н Александров, В.В. Борисов, Г.С. Каплан и др.]; под ред. Г.Н. Александрова. – [2–е изд., перераб и доп.] – СПб.: Изд-во СПбГТУ, 2000. – 540 с.

8. Буткевич Г.В. Задачник по электрическим аппаратам / Буткевич Г.В., Дегтярь В.Г., Сливинская А.Г. – М.: Высшая школа, 1987. – 232 с.

9. Залесский А.М. Тепловые расчеты электрических аппаратов / А.М. Залесский, Г.А. Кукеков. – Л.: Энергия, 1967. – 380с.

10. Исакеев А.И. Эффективные способы охлаждения силовых полупроводниковых приборов / Исакеев А.И., Киселев И.Г., Филатов В.В. – Л.: Энергоиздат. Ленингр. отд-ние, 1982. – 136 с.

11. IEC 60947-1: 2020 Low-voltage switchgear and controlgear – Part 1: General rules, 2020. – 577 p.

12. IEC 62271-1: 2017 High-voltage switchgear and controlgear – Part 1: Common specifications for alternating current switchgear and controlgear, 2017. – 256 p.

13. Bliznykov A.V. Stationary Thermal Behavior Analysis of Current-Carrying Systems of Power Electric and Electronic Equipment / А.В. Близняков // Електротехніка та електроенергетика. – 2012. – №1. – С. 19–22.

Annex A.
Determining temperature using thermoEMF

Temperatures in lab work are determined with the help of a calibration function given in table A.1 for chromel-copel thermocouples. It was obtained at a cold junction temperature of 273.15 K.

Since a different temperature may be in the laboratory during the measurement process, the thermo-EMF value must be a corrected by addition to the measured thermo-EMF of the value found as follows:

$$e_{\mathrm{th}} = e'_{\mathrm{th}} + e_{\mathrm{th0}},$$

where e'_{th} is the thermo-EMF measured by the device;

e_{th0} is the thermo-EMF, determined according to the calibration table for the temperature of the cold junction (air temperature near the lab setup).

The hot junction temperature of the thermocouple is determined by the value of e_{th} and the calibration function. Air temperature is determined using a laboratory thermometer.

Table A.1 – Calibration characteristic of Chromel-Copel thermocouple

Temperature of hot junction, °C	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
	T h e r m o - E M F									
0	0	0,07	0,13	0,20	0,26	0,33	0,39	0,46	0,52	0,59
10	0,65	0,72	0,76	0,85	0,91	0,98	1,05	1,11	1,16	1,24
20	1,31	1,38	1,44	1,51	1,57	1.64	1,70	1,77	1,84	1,91
30	1,98	2,05	2,12	2,18	2.25	2,32	2,38	2,45	2,52	2,59
40	2,66	2,73	2,80	2,87	2,94	3,00	3,07	3,14	3,21	3,28
50	3,35	3,42	3,49	3,56	3,60	3.63	3,77	3,84	3,91	3,98
60	4,05	4,12	4.19	4,26	4,33	4,41	4,48	4,55	4,62	4,69
70	4.76	4,83	4,90	4,98	5,05	5,12	5,20	5,27	5,34	5,41
80	5,48	5,56	5.63	5,70	5,78	5,85	5,92	5,99	6,07	6,14
90	6,21	6,29	6,36	6,34	6,51	6,58	6,65	6,73	6,80	6,87
100	6,95	7,03	7.10	7,17	7.25	7.32	7,40	7,47	7.54	7,62
110	7,69	7.77	7,84	7,91	7,99	8,06	8,13	**8,21**	8,28	8,35
120	8,43	8,50	8,58	8,65	8,73	8,80	8,88	**8,95**	9,03	9,10
130	9,18	9,25	9.33	9,40	9,48	9,55	9,63	9,70	9,78	9,85
140	9.93	10,00	10,08	10,16	10,23	10,31	10.38	10,46	10.54	10,61
150	10.69	10.77	10,85	10,92	11,00	11,08	11,15	11,23	11,31	11,38
160	11,46	11,54	11,62	11,69	11,77	11,85	11,83	12,00	12,08	12,16
170	12,24	12,32	12,40	12,48	12,55	12,63	12,71	12,79	12.87	12,95
160	13,03	13,11	13,19	13,29	13,36	13,44	13,52	13,60	13.68	13,76
190	13,84	13,92	14,00	14,08	14,16	14,25	14,33	14,41	14,49	14,57
200	14,65	14,73	14.81	14,89	14,98	15,06	15,14	15,22	15,30	15,38
210	15,47	15,55	15,63	15,71	15,79	15.88	15,56	16,04	16,12	16,20
220	16,29	16,37	16,45	16,53	16,61	16,70	16,78	16,86	16,94	17,02
230	17,11	17,19	17,27	17,36	17,44	17,52	17,61	17,69	17,77	17,86
240	17,94	18,02	18.10	18,18	18,27	18,35	18,43	18,51	18,60	18,68
250	18.76	18,84	18.82	19,01	19,09	19,17	19,26	19,34	19,42	19,51

Annex B.
Calculation of heat transfer coefficients of rectangular fins

Nusselt and Grashof numbers are calculated using the following formulas:

$$Nu_{\mathrm{m}} = \frac{1}{24} \cdot \frac{w}{L} \cdot (Pr \cdot Gr)_{\mathrm{m}} \left[1 - \exp\left(-\frac{35}{(Pr \cdot Gr)_{\mathrm{m}} \frac{w}{L}} \right) \right]^{0,75};$$

$$Gr_{\mathrm{m}} = \frac{g w^3 \beta}{\nu_{\mathrm{m}}^2} (\vartheta_{\mathrm{s}} - \vartheta_0),$$

where w is the gap width between the fins near the heat sink basement, m;

L is the fin length in the direction of the airflow, m;

Pr is the Prandtl number equal to 0.7 for air;

g – gravitation acceleration, m/s^2;

β is the volume expansion coefficient of air, K^{-1};

ν is the coefficient of kinematic viscosity, which is calculated according to the following formula:

$$\nu = 10^{-9} \frac{(\vartheta_{\mathrm{m}} + 273)^{1,75}}{1,387}, \ \mathrm{m^2/s};$$

ϑ_s is the average surface temperature, °C;

ϑ_0 is the air temperature, °C.

Convective heat transfer coefficient

$$\alpha_{\kappa} = \frac{Nu_{\mathrm{m}} \lambda_{\mathrm{m}}}{w},$$

where λ is the thermal conductivity of air, which is determined by the following formula:

$$\lambda_{\mathrm{m}} = 1,95 \cdot 10^{-4} (\vartheta_{\mathrm{m}} + 273)^{0,861}, \ \mathrm{W/(m \cdot K)}$$

m is the index that indicates that this parameter is taken at the characteristic temperature, which is usually defined as:

$$\vartheta_{\mathrm{m}} = \frac{\vartheta_{\mathrm{s}} + \vartheta_0}{2}.$$

The radiative heat transfer coefficient of the fins and other surfaces of the radiator:

$$\alpha_в = 5{,}67 \cdot 10^{-8} \sigma \frac{(\vartheta_s + 273)^4 - (\vartheta_0 + 273)^4}{\vartheta_s - \vartheta_0} \varphi$$

where σ is the emissivity of the body surface;

φ is the angular radiation coefficient, which is determined by the following formula

$$\varphi = w \frac{L + 2h}{wL + 2Lh};$$

h is the height of the fins in the direction from the basement of the heat sink to the fin end, m.

Finning efficiency:

$$C_{ef} = \frac{\tanh\left(h\sqrt{\frac{2\alpha_{th}}{\lambda_{hs}\delta_f}}\right)}{h\sqrt{\frac{2\alpha_{th}}{\lambda_{hs}\delta_f}}},$$

where α_{th} is the total heat transfer coefficient from the heat sink surface;

λ_{hs} is the thermal conductivity of the heat sink material, W/(m·K);

δ_f is the thickness of the fins at the basement, m.

Thermal resistance of the heat sink

$$R_{th.hs} = \frac{1}{\alpha_{th} S C_{ef}},$$

where S is the total surface area of the heat sink fins, m^2;

For horizontally located cylinders, the Nusselt number is determined by the following formula:

$$Nu = 0{,}36^{0{,}5} + \left\{ \left(\frac{Gr_d \cdot Pr_d}{300} \right) \Big/ \left[1 + (0{,}5/Pr)^{\frac{9}{16}} \right]^{\frac{16}{9}} \right\}^{\frac{1}{6}}.$$

For vertically located cylinders:

$$Nu = C_2 \left(Gr_d Pr_d \cdot \frac{d}{l} \right)^{n_2},$$

where *d* is the diameter of the cylinder, m;

l is the length of the cylinder, m;

C_2, n_2 are coefficients; their values are given in table D2.1.

Table B.1 – Values of the coefficients C_2, n_2.

$\left(Gr_d Pr_d \frac{d}{l}\right)$.	C_2	n_2
10^{-4}–0,05	0,87	0,8
0,05–10^4	1,3	0,36
>10^4	0,57	0

Annex C.
Circuit diagram of the device for measuring temperature

The device for measuring the temperature on the surface of investigated components is a digital thermometer; its circuit diagram is given in Figure C.1. The main components of the thermometer are LM35B temperature sensor, PV millivoltmeter and GB power supply.

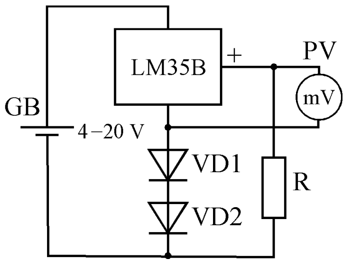

Figure C.1 – Схема цифрового термометра

The thermo-resistive semiconductor LM35CZ/NOPB temperature sensor provides a working temperature range from –40 to +150°C (10 mV/K) with accuracy to 0.1°C. Any digital millivoltmeter with a sufficiently high input resistance can be used as a voltmeter (including an inexpensive Chinese-made multimeter). When measuring temperature, you need to set the measuring range of the voltmeter to 2 V (2000 mV). A "Крона" type element or three finger batteries connected in series can be used as a power source.

The circuit also contains diodes VD1 and VD2 (silicon diodes KD509, KD521, etc. are used), as well as resistor R (18 kΩ). It should be noted that a simplified circuit that does not contain these elements could be used to measure positive temperatures.