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PRIKAZ ISPITIVANJA ELEKTRIČNIH SVOJSTAVA BAKRA I USPOREDBA SA SVOJSTVIMA OSTALIH MATERIJALIMA

PRESENTATION OF THE ELECTRICAL PROPERTIES TESTING OF COPPER AND COMPARISON WITH THE PROPERTIES OF OTHER MATERIALS

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ABSTRACT

The paper compares the properties of copper and its alloys with those of other materials. Copper is one of the most frequently used materials in electrical engineering, precisely due to its combination of electrical and mechanical properties, as well as its economic acceptability. It is primarily employed in the manufacturing of conductors. The aim of this study is to examine the use of copper as a conductor in comparison to some other materials or alloys for the same purpose. The measurement results demonstrate that copper has the best electrical conductivity among the materials tested. Additionally, it has been observed that the addition of impurities to copper degrades the essential electrical properties required for its use as a conductor. To assess the properties of copper, steel, and steel materials, a test model equipped with all the necessary measuring and testing equipment was employed.

Keywords: *copper, wire, electrical resistance, temperature coefficient of electrical resistance, temperature*

1. UVOD
1. INTRODUCTION

Due to its properties, copper, as a chemical element [1, 2], stands out as one of the most frequently used materials in electrical engineering and its branches. Second only to silver [1, 2], copper is the best conductor of heat and electricity. Given its greater abundance in the Earth's crust compared to silver, it enjoys wider commercial use. Until recently, copper held the position of the second most important metal for engineering after iron; in terms of general engineering importance, it ranks just below aluminum [2, 3]. In its pure state, copper is relatively soft, making it easy to work with, and it is also tough and highly ductile. It exhibits excellent technological properties, allowing it to be forged, rolled (at hot and cold temperatures), and drawn into very thin wires. Additionally, it can be welded, and both hard and soft soldered. Pure copper and its alloys [1, 2] find applications in the manufacturing of electrical cables, electrical machines, and transformers. Furthermore, copper alloys are widely utilized in various sectors and industries such as shipping, aviation, and art. Recently [3], there has been a significant increase in the consumption of copper in the production of very thin films for printed and integrated circuits. Copper is also used in the production of various semi-finished products [2] such as wires, sheets, tubes, profiles, and foils. It is employed in the manufacture of high-current conductors and, increasingly, in overhead power lines. Like most metals, the properties of copper change with fluctuations in temperature. Part of this work focuses on investigating the electrical properties of copper and comparing them with those of other materials.

The laboratory tests utilized the following materials in the form of wire: enameled copper wire, steel wire with PVC insulation, and NiChrome wire. The measurements included a dummy designed to test electrical properties with increasing temperature, along with all the necessary measuring and testing equipment. The thesis concludes with the presentation of test results in tabular and graphical forms, followed by a discussion of the findings.

2. OPIS KORIŠTENIH UREĐAJA ZA MJERENJE UTJECAJA TEMPERATURE NA ELEKTRIČNE VELIČINE

2. DESCRIPTION OF THE DEVICES USED TO MEASURE THE INFLUENCE OF TEMPERATURE ON ELECTRICAL QUANTITIES

Korištena mjerna oprema / Used measuring equipment: VOLCRAFT LCR-300 measuring instrument (for measuring resistance) [4], VOLCRAFT PL-120 T1 measuring instrument (for measuring temperature) [5], CONRAD PS-302A laboratory power source (for supplying power to the heater) [6] and a model for carrying out the laboratory tests. Figures 1 and 2 depict the measuring devices used, while Figure 3 illustrates the laboratory power source.

Slika 1 *Mjerni instrument VOLCRAFT LCR-300.*

Figure 1 *Measuring instrument VOLCRAFT LCR-300.*

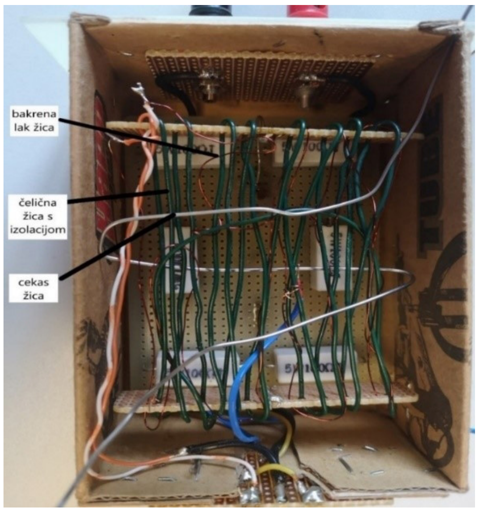
Slika 2 *Mjerni instrument VOLCRAFT PL-120 T1.*

Figure 2 *Measuring instrument VOLCRAFT LCR-300.*

Slika 3 *Laboratorijski izvor napajanja CONRAD PS-302A.*

Figure 3 *Laboratory power source CONRAD PS-302A.*

Figure 4 illustrates the laboratory setup with test wires. The laboratory test is conducted under controlled conditions in a mock-up (constructed from a cardboard box) serving as a heating chamber. Key components of the model include a temperature sensor for measuring the room's temperature and a Vitroplast cover to prevent heat loss within the model. The primary objective is to establish optimal conditions and minimize errors, ensuring a reliable measurement. Efforts are made to prevent cooling of the air inside the model, creating a uniform temperature atmosphere. Weights on the Vitroplast lid further mitigate environmental influences on the measurement. This approach aims to ensure that the temperature of the wire inside the dummy closely corresponds to the temperature indicated by the sensor in the test chamber.



Slika 4 *Laboratorijska maketa sa ispitnim žicama.*

Figure 4 *Laboratory model with test wires.*

It is crucial to position the sensor approximately in the middle of the wire. The objective of this measurement is to acquire the mean (average) temperature value for the observed wire. In the model, the wires are wound in a crosswise manner, forming a zigzag pattern from top to bottom. It is essential to take precautions to prevent non-insulated wires from touching each other, as this contact can potentially influence the measurement results.

3. OPIS MJERENIH ELEKTRIČNIH VELIČINA

3. DESCRIPTION OF MEASURED ELECTRICAL QUANTITIES

The electrical quantities tested in this measurement are electrical resistance R, electrical resistance or specific electrical resistance ρ, and the temperature coefficient of electrical resistance (resistance) α.

a) Electrical resistance *R* [1-3] depends on the length l, cross-section S and conductor temperature T, and is calculated according to the expression:

$$R \quad \frac{\rho \cdot l}{S} \quad [\Omega] \tag{1}$$

where are:

ρ - specific electrical resistance $[\frac{\Omega \mathrm{mm}^2}{\mathrm{m}}]$

S - cross-sectional area of the conductor [mm^2]

l - conductor length [m].

b) Electrical resistance or specific electrical resistance *ρ* [1-3]: This property, assigned to a homogenous material of agreed dimensions at a specified temperature when subjected to direct electric current, is calculated according to the following expression:

$$\rho = \frac{R \cdot S}{l} \quad \left[\frac{\Omega mm^2}{m}\right] \tag{2}$$

c) Temperature coefficient of electrical resistance (resistance) α [1-3]: This value describes the change in resistance of 1 Ω for a temperature change of 1 °C. It is calculated using the expression for the conductor resistance (R_T) at temperature (T):

$$R_T = R_0 \cdot (1 + \alpha \cdot \Delta T) \tag{3}$$

where are:

R_0 [Ω] - conductor resistance at room temperature

R_T [Ω] - conductor resistance at a certain measured temperature

ΔT [°C] - temperature difference

so, the temperature coefficient of electrical resistance is α:

$$\alpha = \frac{1}{\Delta T} \cdot (\frac{R_T}{R_0} - 1) \tag{4}$$

The electrical resistance and the temperature coefficient of electrical resistance depend on the added impurities [1, 2]. Pure metals exhibit the lowest resistance, while the introduction of impurities increases this resistance. In some cases, by elevating the proportion of impurities, the temperature coefficient of electrical resistance may assume a negative value (e.g., with resistant materials) [1]. The anticipated measurement errors attributable to imperfections are estimated to be in the order of 10 to 20%.

d) Standard deviation (σ) is a measure used to quantify the fluctuation or dispersion of the values in a data set. A low standard deviation indicates that the data points are generally close to the expected value of the data set, while a high standard deviation suggests that the data points are scattered over a larger range of values. It is calculated according to the following expression:

$$\sigma = \sqrt{\frac{\sum_{1=1}^{n}(R_i - \bar{R})}{n-1}} \tag{5}$$

where are:

n – number of measured points

R_i [Ω] - conductor resistance in the i-th measurement point

$\bar{R}$ [Ω] – mean value of conductor resistance in all measured points.

e) Relative measurement error (Δ) serves to quantify the measurement results, indicating the accuracy of the measurement. A smaller value corresponds to a more accurate measurement. It is calculated according to the following expression:

$$\Delta = \frac{|\bar{R} - R_i|_{max}}{\bar{R}} \cdot 100\ \% \quad (6)$$

where are:

$|\bar{R} - R_i|_{max}$ [Ω] – the absolute value of the maximum difference between the mean value of the measurement and the measurement at the i-th point.

Cilj pokusa / The aim of the experiment: to practically verify the dependence of electrical quantities on temperature, focusing on the most commonly used conductor material, copper. Additionally, the study will explore this dependence for select materials commonly employed in electrical engineering.

4. OPIS PROVEDENOG POKUSA – MJERENJE OTPORA LCR INSTRUMENTOM

4. DESCRIPTION OF THE EXPERIMENT – RESISTANCE MEASUREMENT WITH THE LCR INSTRUMENT

On the work table (measuring station), there is a test dummy used for conducting measurements. The dummy is equipped with terminals for the power supply of the heater, connected with banana cables, and an output terminal leading from the temperature sensor (thermocouple type K) to the thermometer (see Figure 6). The entire measuring setup is displayed in Figure 6.

The experiment, as outlined in reference [3], involves the following steps:

1. It is necessary to check checking the calibration of the VOLCRAFT LCR-300 digital universal instrument. This is done by shorting the two ends of the cable leads with alligator clips, instead of relying on the instrument's self-calibration. If a value is determined, a correction factor corresponding to this value must be introduced during the subsequent measurements.

2. For each wire under testing, the electrical resistance must be measured at room temperature (assumed to be the temperature of the room at that time). This temperature is denoted as the initial temperature ϑ0. The VOLCRAFT LCR-300 instrument is employed for this measurement.

3. The measurement is then extended to higher temperatures by activating additional measuring devices. To achieve this, use a heater (powered by the CONRAD PS-302A laboratory power supply). Measure the electrical resistance for each tested wire at temperatures of 40, 60, and 80 °C.

Remarks:

- The measurement should be repeated a total of five times, and the average value calculated from these results to enhance the reliability of the measurement outcomes.

- The temperature is measured using a VOLCRAFT PL-120 T1 digital thermometer.

- As heating is a dynamic process, and the temperature changes constantly during heating, it is necessary to measure the electrical resistance at a temperature slightly lower than the desired temperature. For instance, if the resistance is measured at 40 °C, the resistance measurement should start at a temperature of 39.5 °C to eliminate the delay time in the measurement.

- Set the initial supply voltage to a value of 21 V. When the temperature reaches 40 °C, increase the voltage to 27 V. As the temperature rises to 60 °C, change the supply voltage to 30 V. When changing the supply voltage, ensure a sufficiently slow temperature change to achieve a value as close as possible to the desired temperature. This ensures that the tested material is in the heated air long enough to reach approximately the same temperature, improving measurement conditions.

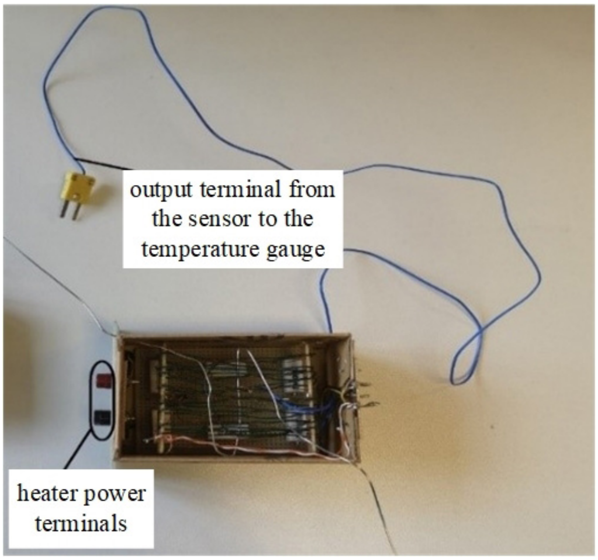
Record the values of the measured resistances at the required temperatures (and specified supply voltages) in a table.

- Based on the measured values of the electrical resistance of the tested wires at the required temperatures, and using expressions (2) and

(4), calculate the electrical resistance (ρ) and the temperature coefficient of the electrical resistance (α). Display the calculated and measured values in a tabular record and a diagram as a function of the temperature ($R = f(\vartheta)$, $\rho = f(\vartheta)$, $\alpha = f(\vartheta)$).

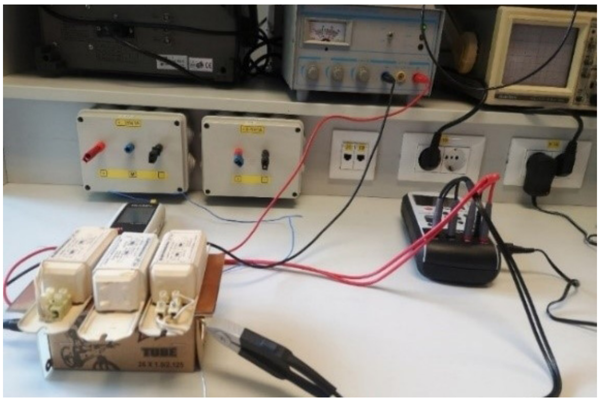
- The results of the measurement of the length, diameter, and calculated cross-sectional areas of the tested wires are shown in Table 1. In this experiment, the properties of the following electrical materials were tested in the form of wires: enamelled copper wire, steel wire with PVC insulation, and NiChrome wire.

- At the conclusion of the measurements, calculate the values of the standard deviation (σ) and the relative measurement error (Δ).



Slika 5 *Prikaz ispitne makete s terminalima.*

Figure 5 *Display of the test model with terminals.*



Slika 6 *Cjelokupna mjerna linija.*

Figure 6 *The entire measurement line.*

Tablica 1 *Prikaz mjerenih i izračunatih vrijednosti za pojedine materijale.*

Table 1 *Display of measured and calculated values for individual materials.*

	copper wire	**steel wire**	**NiChrome wire**
Length l [mm]	1500	3500	300
Diameter d [mm]	0,3	0,5	1
Cross-section area S [mm^2]	0,0707	0,1963	0,7854

4.1. IZMJERENE I IZRAČUNATE VRIJEDNOSTI SVOJSTAVA ZA BAKRENU LAK ŽICU

4.1. MEASURED AND CALCULATED VALUES FOR PROPERTIES OF COPPER LACQUER WIRE

The measured values of the electrical resistance for the copper light wire at specific test

Tablica 2 *Izmjerene vrijednosti električnog otpora pri ispitivanoj temperaturi u 5 točaka (Ri) i izračunata srednja vrijednost $\bar{R}$, standardna devijacija σ i mjerna nesigurnost.*

Table 2 *Measured values of electrical resistance at the tested temperature in 5 points (Ri), calculated mean value $\bar{R}$, standard deviation (σ) and measuring uncertainty.*

Temperature ϑ [°C]	**Measured electrical resistance R_i [Ω]**					**$\bar{R}$ [Ω]**	**$\sigma(R_i)$**	**Δ [%]**
	R1	R2	R3	R4	R5			
28	0,238	0,238	0,237	0,236	0,239	0,238	0,00123	0,84034
40	0,248	0,248	0,247	0,246	0,249	0,248	0,01079	0,80645
60	0,263	0,263	0,261	0,260	0,264	0,262	0,02711	0,83905
80	0,280	0,280	0,279	0,278	0,282	0,280	0,04676	0,71429

temperatures (Ri), obtained at five points, are listed in Table 2. The same table also displays the data for the calculated mean value of the electrical resistance ($\bar{R}$).

The temperature coefficient of electrical resistance is calculated using expression (4). The calculated values of the temperature coefficient of electrical resistance (α) for temperature intervals (Δϑ) are tabulated in Table 3.

Tablica 3 *Izračunate vrijednosti temperaturnog koeficijenta električne otpornosti prema promjeni ispitivane temperature.*

Table 3 *Calculated values of the temperature coefficient of electrical resistance according to the change of the tested temperature.*

Δϑ [°C]	***α* [1/°C]**
40 - 28	0,00350
60 - 40	0,00302
80 - 60	0,00323
80 - 28	0,00394

4.2. IZMJERENE I IZRAČUNATE VRIJEDNOSTI SVOJSTAVA ZA ČELIČNU ŽICU

4.2. MEASURED AND CALCULATED VALUES FOR PROPERTIES OF STEEL WIRE

The measured values of the electrical resistance for the steel wire at specific test temperatures (R_i), obtained at five points, are listed in Table 4. The same table also displays the data for the calculated mean value of the electrical resistance ($\bar{R}$).

Similar to the previous case, the temperature coefficient of the electrical resistance is calculated using expression (4), and the calculated values are listed in Table 5.

Tablica 5 *Izračunate vrijednosti temperaturnog koeficijenta električne otpornosti prema promjeni ispitivane temperature.*

Table 5 *Calculated values of the temperature coefficient of electrical resistance according to the change of the tested temperature.*

Δϑ [°C]	***α* [1/°C]**
40 -28	0,00405
60 - 40	0,00369
80 - 60	0,00360
80 - 28	0,00398

4.3. IZMJERENE I IZRAČUNATE VRIJEDNOSTI SVOJSTAVA ZA CEKAS ŽICU

4.3. MEASURED AND CALCULATED VALUES FOR PROPERTIES OF NICHROME WIRE

The measured values of the electrical resistance for the NiChrome wire, measured at 5 points at a specific test temperature (R_i), are listed in Table 6. The same table also shows the data for the calculated mean value of the electrical resistance $\bar{R}$.

Similar to the two previous cases, the temperature coefficient of the electrical resistance is calculated using expression (4), and the calculated values are presented in Table 7.

Tablica 4 *Izmjerene vrijednosti električnog otpora pri ispitivanoj temperaturi u pet točaka (Ri) i izračunata srednja vrijednost $\bar{R}$.*

Table 4 *Measured values of electrical resistance at the tested temperature in five points (Ri) and calculated mean value $\bar{R}$.*

Temperature *ϑ* [°C]	**Measured electrical resistance *R* [Ω]**					**$\bar{R}$ [Ω]**	**$\sigma(R_i)$**	***Δ* [%]**
	R1	R2	R3	R4	R5			
28	0,555	0,555	0,556	0,557	0,554	0,555	0,35487	0,18018
40	0,582	0,582	0,583	0,584	0,581	0,582	0,38505	0,17182
60	0,625	0,624	0,625	0,626	0,623	0,625	0,43223	0,32
80	0,670	0,670	0,671	0,671	0,669	0,670	0,48322	0,14925

***Tablica 6** Izmjerene vrijednosti električnog otpora pri ispitivanoj temperaturi u 5 točaka (Ri) i izračunata srednja vrijednost $\bar{R}$.*

***Table 6** Measured values of electrical resistance at the tested temperature in 5 points (Ri) and calculated mean value $\bar{R}$.*

Temperature ϑ [°C]	**Measured electrical resistance R [Ω]**					**$\bar{R}$ [Ω]**	**σ(Ri)**	**Δ [%]**
	R1	R2	R3	R4	R5			
28	0,569	0,569	0,568	0,568	0,569	0,569	0,36962	0,17575
40	0,568	0,569	0,568	0,567	0,569	0,568	0,36918	0,17606
60	0,567	0,568	0,567	0,567	0,568	0,567	0,36828	0
80	0,568	0,568	0,568	0,567	0,569	0,568	0,36895	0,17606

***Tablica 7** Izračunate vrijednosti temperaturnog koeficijenta električne otpornosti prema promjeni ispitivane temperature.*

***Table 7** Calculated values of the temperature coefficient of electrical resistance according to the change of the tested temperature.*

$\Delta\vartheta$ [°C]	**α [1/°C]**
40 -28	-0,00013
60 - 40	-0,00009
80 - 60	-0,00009
80 - 28	-0,00003

5. DISKUSIJA DOBIVENIH REZULTATA

5. DISCUSSION ON OBTAINED RESULTS

Initially, the discussion focuses on the relationship between the calculated and measured data for the resistance change, as presented in Table 8.

***Tablica 8** Izračunate vrijednosti odnosa računski i mjereno dobivenog podatka za odnos promjene otpora.*

***Table 8** Calculated values of the ratio of calculated and measured data for the ratio of the change in resistance.*

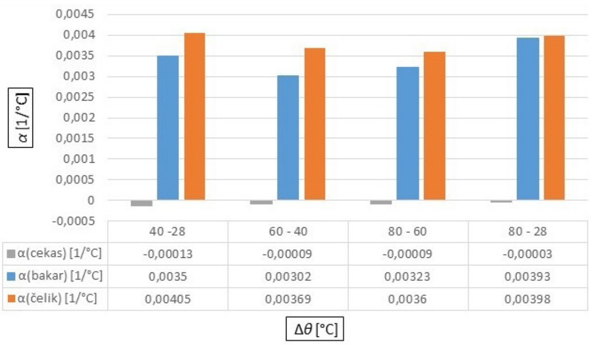
Material	$\frac{R_T/R_0\,(numerical)}{R_T/R_0\,(measured)}$
Cooper	1,023
Steel	1,052
NiChrome	1,009

The disparity observed in the difference between the calculated and measured ratios of resistance change $\frac{R_T/R_0\,(numerical)}{R_T/R_0\,(measured)}$ in copper and steel wires, concerning temperature change, can be attributed to the variance between the temperature registered by the sensor and the actual temperature of the wire. In the case of NiChrome wire, this difference is comparatively smaller, given its minimal (almost negligible) change in resistance with temperature variations.

Below is a comparison of two other electrical quantities of materials: the temperature coefficient of electrical resistance (α) and electrical resistance (ρ).

In Figure 7, the diagram presents a comparison of the temperature coefficients of electrical resistance for the tested materials. It is evident that copper exhibits a lower temperature coefficient than steel, although this difference diminishes with greater temperature change (Δϑ). The temperature coefficient also provides insights into the material's resistance characteristics. Copper has a higher positive temperature coefficient than steel, indicating that the resistance of copper increases more with rising temperature. Conversely, NiChrome demonstrates a negative temperature coefficient of electrical resistance, albeit very small, resulting in a slight decrease in resistance with increasing temperature. This characteristic makes NiChrome suitable for use in the production of heating appliances.

The calculated values of electrical resistance (using expression (2)) for the tested materials are presented in Table 8. From the obtained values, it is evident that copper and steel belong to the group of conductive materials, while copper is classified as a resistive material.



***Slika** 7 Dijagramski prikaz vrijednosti temperaturnog koeficijenta otpornosti za ispitivane materijale.*

***Figure** 7 Schematic representation of the value of the temperature coefficient of resistance for the tested materials.*

6. ZAKLJUČAK I MOGUĆI SMJEROVI BUDUĆIH ISTRAŽIVANJA

6. CONCLUSION AND POSSIBLE DIRECTIONS OF FUTURE RESEARCH

In practice, copper is widely recognized as the material with the best electrical and thermal conductivity after silver. Its frequent use in electrical engineering is attributed to its optimal combination of electrical, mechanical properties, and economic viability.

When employing the LCR measurement method with a measuring device, selecting a wire with the correct diameter is crucial. Optimal wire diameter is desirable, aiming for it to be as small as possible. For some materials, resistance can be so low that it falls outside the measuring range of the meter used. It's advisable to calculate expected resistances before the actual measurement to ensure accuracy, or consider alternative methods if needed.

The tests utilized various materials in the form of wire, including enamelled copper wire, steel wire with PVC insulation, and NiChrome wire. To conduct the measurements, a dummy was created to test the electrical properties of the material with increasing temperature. All required measuring and testing equipment was employed.

The article presents a comparison of the temperature coefficients of electrical resistance (αα) for the investigated materials, along with the values of electrical resistance (ρρ). Additionally, it provides an overview of the relationship between the calculated and measured data for the change in resistance of these materials.

Subsequent investigations will focus on comparing copper with other alloys, specifically brass and solder.

Priznanje / Acknowledgment

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***Tablica 9** Izračunate vrijednosti električne otpornosti ρ za ispitivane materijale.*

***Table 9** Calculated electrical resistance values (ρ) for the tested materials.*

Temperature ϑ [°C]	Electrical resistance of copper ρ_{Cu} [Ω/mm²]	Electrical resistance of steel $\rho_{Č}$ [Ω/mm²]	Electrical resistance of NiChrome ρ_{c} [Ω/mm²]
28	0,0113	0,0311	1,4896
40	0,0118	0,0326	1,4870
60	0,0124	0,0351	1,4844
80	0,0133	0,0376	1,4870

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