Mathematical simulation of thermocouple characteristics

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Abstract. Within this article, the investigation of the electrical characteristics of two thermocouples in parallel connection was mathematically simulated for further research of the effect of multi-point contact between the sensing thermocouple electrodes and the inspected sample in thermoelectric inspection devices.

1. Introduction

Thermoelectric method is implemented extensively in the area of non-destructive testing of metals and alloys in applications that require sorting and verification procedures [1-3]. The thermoelectric testing method is good for many applications such as the checking of a decarburized layer of steel surfaces [4], resolving the thickness of steel cemented layers [5], separation of the finished product according to sorts [6] and plastic deformations testing [7]. However, the results obtained from thermoelectric performed inspections are generally unreliable due to the roughness and heterogeneity of the surface and also the existence of plastic deformation in the inspected object, which all result in a multipoint contact [8]. The impact of the interface on testing results is specified in the works [9, 10]. To consider such factors in the inspection process, it is important to study the extent of impact of these aspects on the evaluation results. A good way to study these aspects is by replicating the heterogeneous surface by experimental types of thermocouples of different materials [11]. For this target, it is essential to develop a mathematical model that is capable of determining the thermoelectric characteristics. The model should be able to check the thermoelectric characteristics of experimental thermocouples at various temperatures considering the load resistance. The experimentation of wide ranges of temperatures is essential to determine the optimum temperature with the best power quality in order to reach good thermoelectric testing results. However, modifying values of the load resistance are important in order to reach the degree of impact, which is motivated by the contact resistance of hot and cold electrodes of thermoelectric inspection devices, on the evaluation results, upon handheld testing.

Simulating the experimental results of the thermopower-resistance dependency helps with forming an analytical expression that can be used for later mathematical modulation, which eventually helps improve the testing parameters and hence the thermoelectric testing qualities of TEMF devices [11, 12].
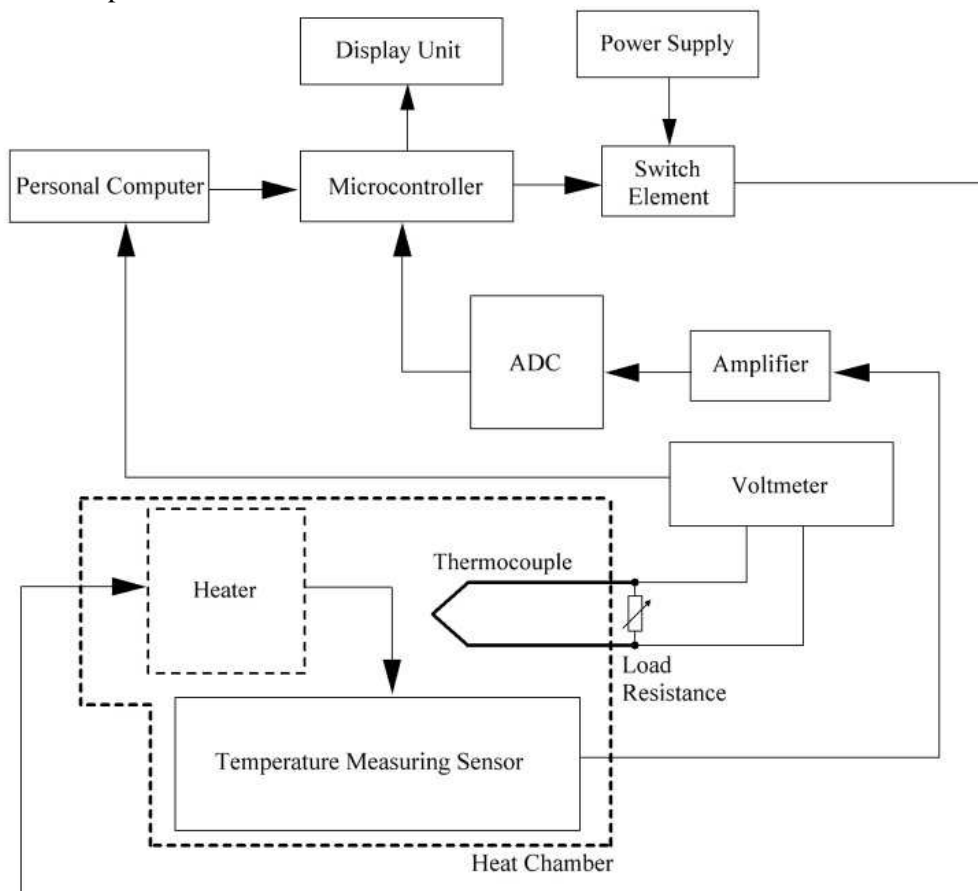
2. Experimental Setup

In this study, several parallel thermocouples are investigated in a temperature range of (100°C - 300°C).

The experimental setup is shown in Fig. 1 in the block diagram and consists of:
- Thermocouples;
- Heat chamber;
- Heat chamber control system;
- Toggle switch panel (nominal values of 0.01Ω, 0.05Ω, 0.1Ω, 0.5Ω, 1Ω, 3.3Ω, 6.8Ω, 10Ω, 50Ω, 100Ω, 1kΩ, 10kΩ);
- Measuring voltmeter;
- Personal Computer.

Figure 1. Block diagram of experimental setup.

The schematic diagram of the experimental setup is demonstrated in Fig. 2. The experimented thermocouple is represented in the diagram (Fig. 2) as voltage sources 'E' along with internal resistance 'r'. Investigated thermocouples (Chromel-Alumel & Nichrome-Constantan) are alternately located in the chamber at temperature values ranging from 100°C to 300°C. The measurement of the voltage drop across the load resistance 'R' is thoroughly taken.

Measurements are taken in case of single and parallel connection of thermocouples with the load resistance 'R'. The investigated nominal values of the load resistance are 0.01Ω, 0.05Ω, 0.1Ω, 0.5Ω, 1Ω, 3.3Ω, 6.8Ω, 10Ω, 50Ω, 100Ω, 1kΩ, and 10kΩ. Calculations of the thermoelectric power, the internal resistance, the flowing current in the circuit, and the maximum electric power were all carried out [8] and simulated.
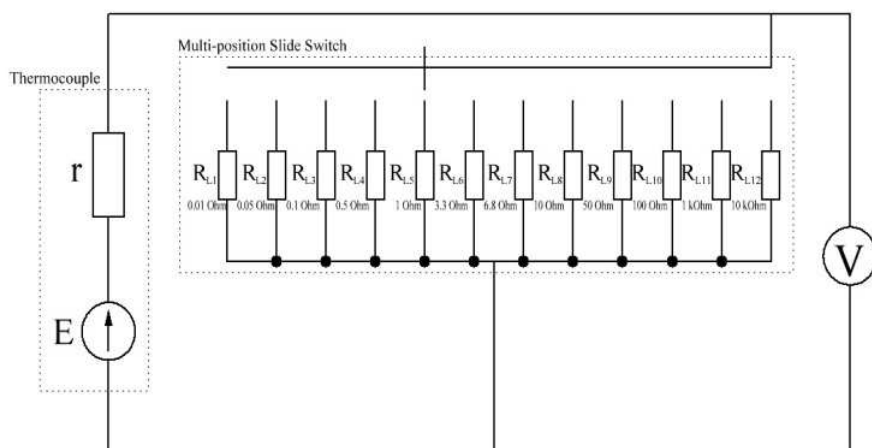
Figure 2. Schematic diagram of experimental setup: E is the source of thermopower,
r is internal resistance, $R_{L1}…R_{L12}$ are load resistances, V is the voltmeter.

3. Experimental results

The results of the measured voltage across the load for the three temperature values are presented in
Fig. 3. Fig.3.a shows the investigated characteristics of thermocouple Chromel-Alumel. Fig.3.b shows
the investigated results of Nichrome-Constantan. Fig.3.c shows the case for their parallel connection.
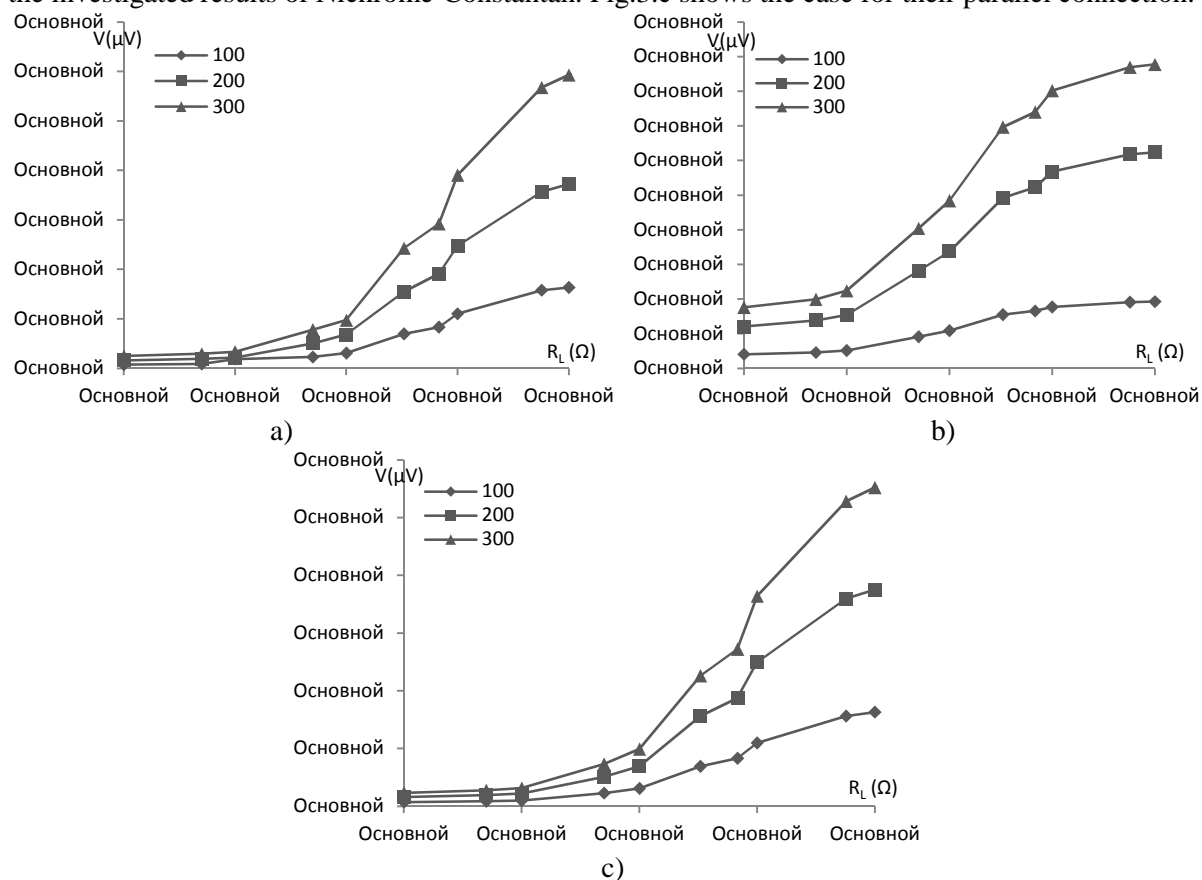

Figure 3. The dependence curves at a logarithmic scale of the load voltage on the load resistance
under various connections of thermocouples at temperature (100 to 300)°C: a) Chromel-Alumel, b)
Nichrome-Constantan, c) Chromel-Alumel in parallel connection with Nichrome-Constantan.

As shown in the graphs, as the load resistance 'R$_L$' increases, the load voltage 'V$_L$' also increases until it approaches the value of thermoelectric power in the open-circuit condition. Upon the increase in temperature, the value of 'V$_L$' increases as well due to the increase of thermoelectric power, which is proportional to temperature.

Through the investigation of the parallel thermocouples which was conducted in the previous paper [12], it has been found experimentally that the most optimal load resistance for thermocouples is equal to 1Ω. This resistance satisfies the condition 'r=R$_L$' and consequently thermocouple electric power is greatest.

4. Mathematical Simulation

For the numerical analysis of the thermoelectric power experimental results, the interpolation method of the Newton polynomial [13, 14] was used through the algorithm of divided differences. Newton's formula is of interest because it is the straightforward and natural differences-version of Taylor's polynomial [15], which indicates where a function will go, based on its y value and its derivatives (its rate of change, and the rate of change of its rate of change, etc.) at one particular x value.
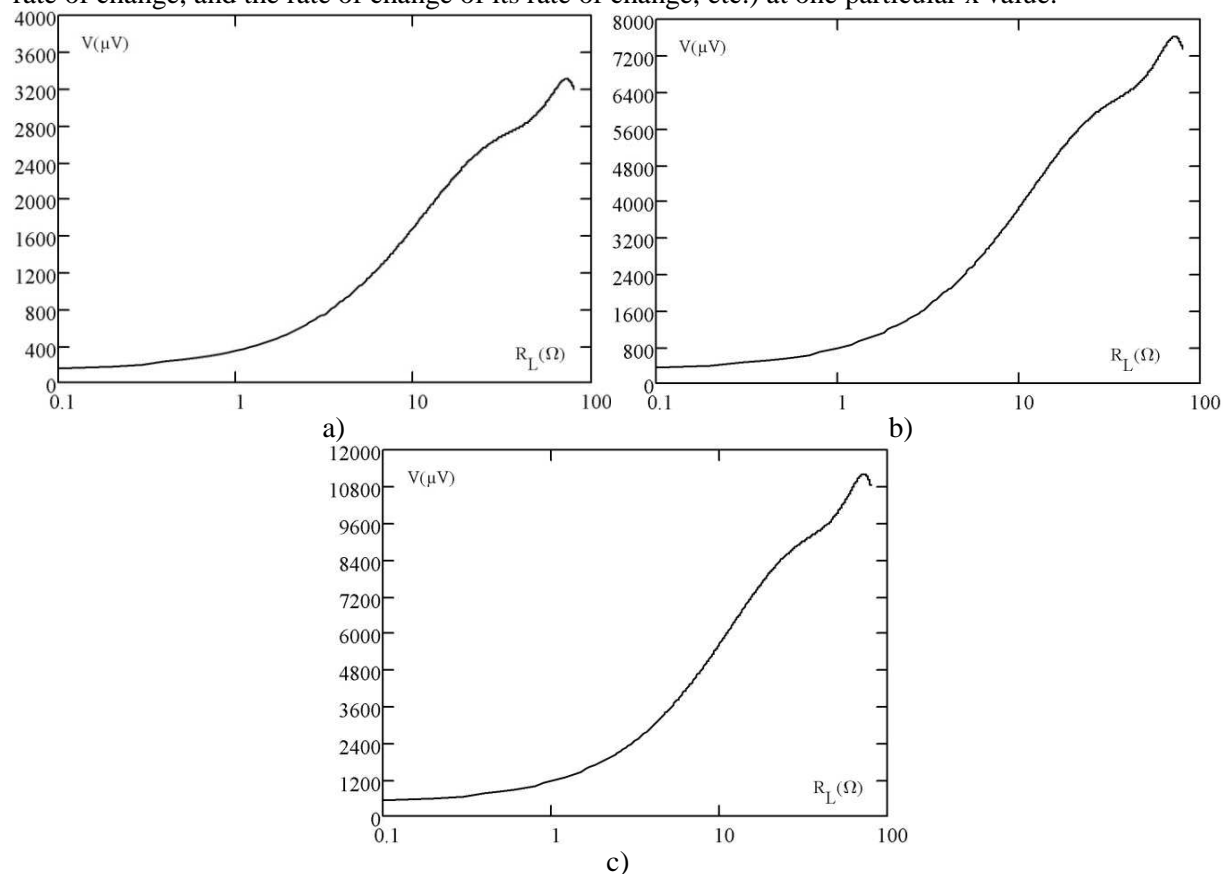
Figure 4. Simulated curves of the thermoelectric power on the resulted parallel connection of Chromel-Alumel & Nichrome-Constantan dependent on the load resistance: a) 100°C, b) 200°C, c) 300°C.

Newton's formula is Taylor's polynomial based on finite differences instead of instantaneous rates of change. Consequently, the newton polynomial for temperatures 100°C, 200°C and 300°C is expressed through the mathematical equations accordingly:

$$V(R_L) = 0.1R_L^3 - 5{,}3 \times 10^{-4}\, R_L^4 - 6.9R_L^2 + 214.6\, R_L + 137.9 \qquad (1)$$

$$V(R_L) = 0.23R_L^3 - 12.1 \times 10^{-4} \, R_L^4 - 15.8R_L^2 + 490.5 \, R_L + 296.6 \qquad (2)$$

$$V(R_L) = 0.34R_L^3 - 17.7 \times 10^{-4} \, R_L^4 - 22.9R_L^2 + 714.1 \, R_L + 444.1 \qquad (3)$$

,where $V(R_L)$ is the thermoelectric power, R_L is the load resistance.

The simulation results in accordance with expressions (1), (2) and (3), are presented in Fig. 4 and they are in good correlation with experimental ones.

From Fig.4.c it can be noticed that the thermoelectric power, in case of thermocouples' parallel connection, is an average equivalent of thermoelectric power of each of Chromel-Alumel and Nichrome-Constantan thermocouples in Fig.4.a and Fig.4.b.

5. Conclusion

The investigation of the parallel thermocouples connection was mathematically simulated. Therefore, it became clear that thermoelectric power values of thermocouples, when connected in parallel, are equivalent to the average values of thermocouples, Chromel-Alumel and Nichrome-Constantan, taken together.

An analytical expression is obtained for the function describing the dependence of the equivalent thermoelectric power of two thermocouples connected in parallel dependent on the load resistance. The analytical expression will be used for further simulation of the thermoelectric method of monitoring multipoint contact of electrodes with an investigated sample.

6. Acknowledgments

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