SELECTED FACTORS AFFECTING THE PRECISION OF THERMOCOUPLES

Peter Pavlasek[1,2], *Stanislav Ďuriš*[1], *Rudolf Palencar*[1]

[1]Slovak University of Technology, Faculty of Mechanical Engineering, Bratislava, Slovakia,peterpavlasek@gmail.com, rudolf.palencar@stuba.sk, stanislav.duris@stuba.sk
[2] Slovak Institute of Metrology, Bratislava, Slovakia, peterpavlasek@gmail.com

Abstract – The importance of precise measurements of various quantities is undeniable, as their values effect many processes in industry and other fields. One of the important quantities measured, that effects a majority of processes is undoubtedly temperature. The following work is focused on selected factors that affects the precision of thermoelectric sensors from noble and base metals. All of the results are put into context with the factors that affect the measurement capabilities of thermocouples.

Keywords: thermocouples, base metal, noble metal, hysteresis, homogeneity

1. INTRODUCTION

Measurements of physical quantities plays an important role in many industrial and non-industrial applications. A vast majority of the measured data directly affect the processes that are crucial for the final products quality. Furthermore the data provide a valuable source of information for further analysis which can result in improving effectiveness, safety and ecology of the process. One of the most commonly measured quantities in wide range of applications is without a doubt temperature. As this quantity affects many biological, metallurgical, electrical and other processes it is of great interest amongst the industry to have reliable and precise measurements of temperature. Temperature measurements can be performed by many different devices with different levels of precision. In this paper we will be focusing on one of the most commonly used temperature sensor in industry, thermocouples. These active sensors are well known for their robust construction, reliability, precision and wide temperature range in which they can operate. The unique property of these sensors is their active way of measuring temperature. This means that the thermocouple itself generates a voltage output which level depends on the exposed temperature. This Seebeck effect on which they operate is both the source of many advantages and disadvantages. The main weakness of this principle is that the amount of generated voltage depends on the material of the wire of the thermocouples and their purity. This means that any impurity or change in lattice structure will result in change in voltage output when the sensor is exposed to identical conditions. This fact is the source of most errors in measurement with these measuring devices and also the source of their higher uncertainty compared to platinum resistance thermometers. In this paper we will be focusing on multiple factors like homogeneity changes caused by mechanical strain exposure, hysteresis effects that are caused by chemical changes at certain temperature intervals, on construction related issues and on long term drift behaviour of thermocouples. In most of these studies we are going to focus on base metal thermocouples Type N and K in mineral insulated metal sheathed configuration (MIMS), but likewise the noble metal Au/Pt thermocouples.

2. MECHANICAL STRAIN EXPERIMENT

Inhomogeneity in industrial conditions mainly arises from changing composition and grain structure of the thermoelements. The latter effect is enhanced under mechanical strain [1, 2, 3]. The most common source of mechanical strain is bending, as thermocouples are commonly bent to reach various places within industrial processes that would be inaccessible otherwise. The uniqueness of this study is that the investigation was performed under condition closes to industrial ones. Unlike in other studies where mainly unsheathed wires were tested the thermocouples tested in this study are in MIMS configuration and therefore represents the most commonly used sensors in industry.

The change of homogeneity due to mechanical strain exposure was investigated on Type N and Type K thermocouples. The mechanical strain was generated by force application by cylindrical and triangular profiles. Cylinders with different diameters were used as well as triangular profiles with different angles. The force was applied separately on different parts of thermocouples and after each application a homogeneity scan was performed in an isothermal oil bath at temperature of 150 °C. The homogeneity measurement was performed after each stain exposure. This was done by fully immersing the thermocouple into the oil bath and slowly withdrawing it in 8.2 mm steps. At each measuring step the thermocouple was left for 90s of equilibrium time and after that the generated voltage from the thermocouple was measured. This was done over a 550 mm length of the thermocouple.

2.1. Resulting effect of mechanical strain on MIMS Type N and K thermocouples.

The most significant effect of the applied mechanical strains on the thermocouple can be seen in Figs.1-2. In these figures the temperature difference from the initial

state(before strain application) is presented. The uncertainty on each of these measurement points has been estimated and its values is 20.2μV (where the coverage factor k = 2). The mechanical strain applied on the Type K thermocouple caused a change in its output by a small but distinct amount. The Type N thermocouples showed no influence of the mechanical strain on homogeneity. The maximum difference observed from the initial homogeneity state was 0.09 °C (3.58 μV) for the 1.0 mm Type K thermocouple bent around a 63 mm diameter circular surface and for angular bending the maximum difference was 0.02 °C (0.87 μV) around an angle of 90°. For the 1.5 mm Type K thermocouple the maximum difference from the initial homogeneity state was the same 0.09 °C (3.52 μV) around a 63 mm diameter bend and for angular bending the maximum difference was 0.05 °C (2.07 μV) around an angle of 90°.
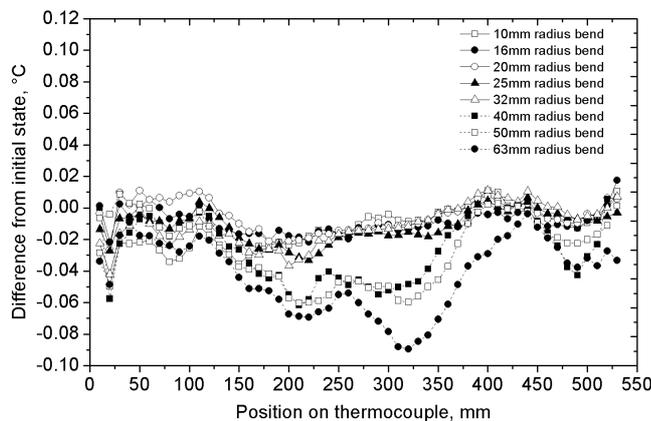

Fig. 1. The temperature difference from initial state measured with a 1.0 mm outer diameter Type K thermocouple, after bending around circular surfaces.
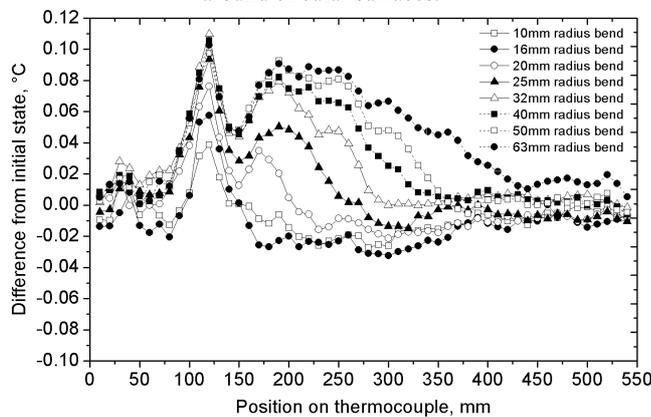

Fig. 2. The temperature difference from initial state measured with a 1.5 mm outer diameter Type K thermocouple, after bending around circular surfaces.

3. HYSTERESIS EXPERIMENT

Hysteresis effects in base metal thermocouples could be significant in industrial applications in which a temperature increase and decrease needs to be monitored continuously. The main issue with hysteresis in base metal thermocouples is that the temperature indicated when heating is not the same as indicated when cooling. This effect was investigated in publications [4-9] where the results suggest that the hysteresis effects in Type K alloys occur at temperatures between 200°C and 600°C and in Type N alloys this effect occurs at a temperature range of 200 °C to 1000 °C. Hysteresis in base metal thermocouples is caused by reversible changes in thermoelement alloys. These changes affect the Seebeck coefficient of the wires and thereby change the thermoelectric response (emf) of the thermocouples. The mechanism causing this hysteretic behaviour in dilute nickel-chromium alloys can be described by electron spin-cluster mechanism which is described by Pollock [10]. The study here presented is performed on thermocouples which were constructed by the newest manufacturing technologies which leads to a conclusion that the hysteresis effect could differ from the previously undertaken studies.

The hysteresis investigation was performed in a horizontal tube furnace in which Type N and K thermocouples were placed and ramped multiple times from 200 °C to 1000 °C. This ramping was performed in 50 °C temperature steps. In each of these steps the voltage output of the tested thermocouples was measured after stabilisation for 40 min. From each temperature step the recorded data was processed into one value which represented the measured temperature at a certain step. A calibrated Type R thermocouple was used as a reference to monitor the furnace stability and the temperature in the vicinity of the tested thermocouples.

3.1. Resulting hysteresis effect on MIMS Type N and K thermocouples.

All of the measured data show almost identical behaviour and a high level of repeatability, which is typically better than 0.6 °C. The standard deviation of the measurements taken after the stabilization period was found to be better than 76.3 μV for the tested thermocouples and better than 17.9 μV for the reference thermocouple. The values of temperature (calculated form thermocouple voltage output) obtained for the Type N and Type K thermocouples were compared to the indicated temperature of the reference Type R thermocouple. In Fig. 3 and 4 a difference between the cooling and heating cycles for each thermocouple is visible in the presented graphs. The magnitude of these differences is small (up to only 1 °C) compared to the repeatability of the measurements, which has been found to be 0.6 °C.
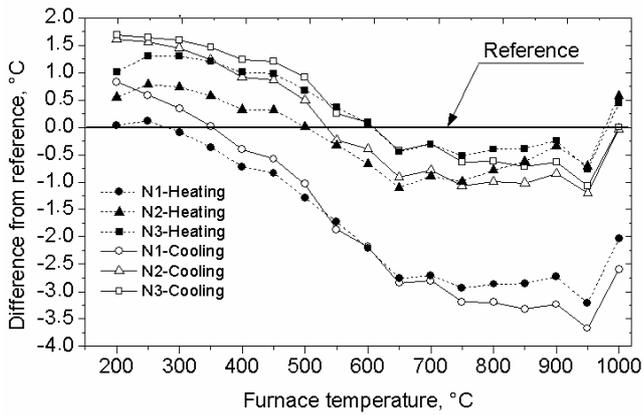
Fig. 3. Measured temperature difference from the reference Type R thermocouple, for three 3.0 mm diameter Type N thermocouples, upon heating (closed points) and cooling (open points).
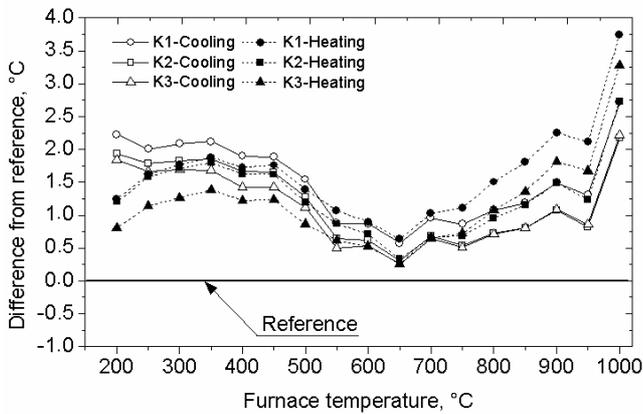

Fig. 4. Measured temperature difference from the reference Type R thermocouple, for three 3.0 mm diameter Type K thermocouples, upon heating (closed points) and cooling (open points).

4. STABILITY EXPERIMENT

Stability of voltage output is a key property and this study focused on Type N and K thermocouples with different wire diameters. Stability issues we are going to deal with are chemically induced changes thus the permanent change in Seebeck coefficient. These permanent changes arise in nickel based thermocouples (type N and K) at temperatures above 600°C. A change in voltage output can be seen when thermocouples without a protective sheathing are exposed to these temperatures. A positive drift can be seen in nickel based thermocouples with metal sheathing and mineral insulation (MIMS) but only at temperatures between 600°C to 900°C. By higher temperatures a significant and constant voltage drop occurs. This behaviour was described in various publication [1, 11, 12] with the same results for type N and type K thermocouples. The mentioned publications describe the process of drift by the migration of particles between the thermocouple thermoelements and the mineral isolation material and the metal sheath. The main source of contamination according to publications [11, 12] is considered manganese (Mn) as the main element that causes

drift. This elements can be found in the sheathing material of the thermocouple and at temperatures over 1100°C it contaminates the thermocouple thermoelements affecting the Seebeck coefficient.

4.1. Resulting drift effect on MIMS Type N and K termocouples.

The drift of the voltage output and diameter relationship was measured on type N thermocouples in MIMS configuration. The sheath material for the tested thermocouples was made of Inconel 600 and with mineral insulation inside the sheath. Eight thermocouples of the highest precision class for the mentioned type with four different outer diameters were tested. These thermocuples were separated into two batches (each consisting of four thermocouples) and were housed in a ceramic tube and placed into a centre of a three zone horizontal tube furnace. To measure the homogeneity profile of the furnace and to monitor the stability of the furnace a calibrated Type R thermocouple was used. The measurements were done at temperatures of 1200 °C and 1250 °C (one temperature for each batch). The test lasted for more than 80 hours (for 1200 °C) and over 200 hours (for 1250 °C). The resulted maximum differences in indicated temperature trough time can be seen in Table 1. Values of temperature decrees and the corresponding wire diameters have been used to establish a drift function. This functions can be seen in Fig. 5. This figure empresses the dependence of average temperature decrees by one hour and the thermoelement diameter when thermocouples are exposed to a temperature of 1250 °C.

Table 1. Maximum temperature difference from the initial state for various thermoelement diameters at 1200°C and 1250°C.

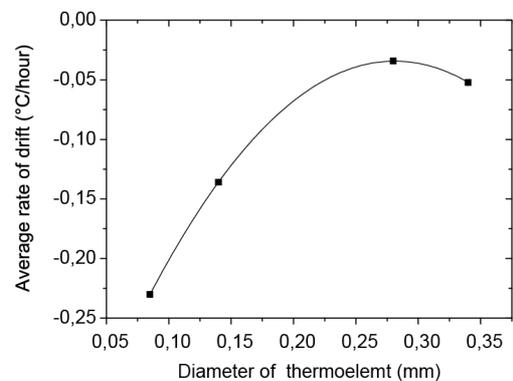| Thermo element wire diameter (mm)	Temperature difference from the initial state after 84 hours at 1200 °C (°C)	Temperature difference from the initial state after 214 hours at 1250 °C (°C)
0.085	- 5	- 25
0.140	- 3	- 14
0.280	- 2	- 7
0.340	- 4	- 8

Fig. 5. Function of type N thermocouple thermoelements diameter and an average temperature decrees in temperature from the initial state after one hour (measured at 1250°C).

5. INVESTIGATION OF DIFFERENT ISOLATION MATERIAL IN PT/AU TERMOCOUPLES

As previously presented thermocouples work on the principles of Seebeck effect and therefore the wire material composition and isolation material affect their performance [1]. This part of the paper is dedicated to platinum gold (Pt/Au) thermocouples which precision is one of the highest of all the commercially produced noble metal thermocouples. The investigation that is presented deals with two types of inner isolation material and their effect on the voltage output of thermocouples.

For this investigation two Au/Pt thermocouple were tested with a quartz glass outer and inner isolation. The measurements were performed in fixed points specifically in freezing points of zinc (419.527 °C), aluminium (660.323 °C) and silver (961.78 °C). Multiple measurements were realised in each fixed points with quartz glass (SiO2) inside isolation and likewise the same procedure was performed with pure alumina (Al$_2$O$_3$ 99.7%) inner isolation.

5.1. Resulting effect of different isolation material on Pt/Au thermocouples.

Results obtained from previously described measurements can be seen in Table 2. From this data we can determine that there is clear difference between the isolation materials used. The increasing difference with temperature can be observed in measurements with both thermocouples. The highest difference for Au/Pt-1 thermocouple at silver fixed point was 6.8 µV (0,27 °C) and for Au/Pt-2 the highest difference was 11.5 µV (0,46 °C). The possible reason for this difference could be the reduced insulation resistance of SiO2 at higher temperatures.

Table 2. Measured Emf (voltage output) at fixed point of Zn, Al and Ag for thermocouples with Quartz glass (quartz) and Alumina (alum.) inner isolation.

Fixed point	Au/Pt -1			Au/Pt -2		
	Emf, µV (quartz)	Emf, µV (alum.)	Δemf, µV	Emf, µV (quartz)	Emf, µV (alum.)	Δemf, µV
Ag	16084.9	16091.7	6.8	16101.6	16113.1	11.5
Al	9299.3	9300.6	1.3	9312.6	9315.0	2.4
Zn	4933.2	4934.0	0.8	4942.6	4943.0	0.4

4. CONCLUSION

In previously described studies a noticeable effect of each factor has been found. This fact confirms the previously indicated problematic of each selected factor on the precision of base and noble metal thermocouples. The most significant effect could be observed during the strain measurements on Type K thermocouples and the final effect of mechanical strain (generated by bending) is up to 0.09 °C. The effects on Type N thermocouples in this matter can be neglected. The hysteresis measurements have shown a maximum difference up to 1 °C (must be put into context with the repeatability of 0.6 °C) for both Type N and K thermocouples. The drift experiment has shown an interesting relationship between the thermocouple diameter and the drift rate. The maximum drift rate was found to be up to -25 °C (for termoelement diameter of 0.085 after 214 hours at 1250 °C) for Type N thermocouple. This result is only valid for a specific termoelement diameter and temperature exposure. The investigation of different isolation materials used in Au/Pt thermocouples has also shown a noticeable effect. The measurements in fixed point have shown that the differences between the quartz glass and alumina inner isolation has a increasing tendency and the maximum difference was found to be up to 0.46 °C at the temperature of 961.78 °C.

REFERENCES

[1] R.E. Bentley,Handbook of temperature measurements, Volume 3:Theory and practice of thermoelectric thermometry, Springer, CSIRO, (1998)

[2] J.F.Potts and D.L. McElroy,inTemperature; Its Measurement and Control in Science and Industry, Vol. 3,ed. by A. I. Dahl, Reinhold Publishing Corp., London,1962, p. 243

[3] D. D. Pollock and D. I. Finch,Temperature; Its Measurement and Control in Science and Industry: The Effect of Cold Working Upon Thermoelements, Vol. 3, ed. by A. I. Dahl, Reinhold Publishing Corp., London, p. 237, (1962)

[4] R.E. Bentley, J. Phys. D: Appl. Phys. **22**(1989)

[5] R. Nordheim,N.J. Grant, J. Inst. Metals **82** 440(1953)

[6] V.A. Callcum,Aging of ChromelAlumel thermocouples, UKAEA report 1021(1965)

[7] G. Coggiola, L. Crovini, A. Mangano, High Temp.-High Pressure**20** 419(1988)

[8] F. Andersen,Proc.TEMPMEKO 2002,Vol. 1, ed. by B. Fellmuth, J. Seidel, G. Scholz, VDE verlag, Berlin (2002), pp. 55-60

[9] N. A. Burley, R. M. Hess, C. F. Howie and J. A. Coleman, Temperature: its Measurement and Control in Science and Industry, Vol. 5, p. 66-1159, Am. Inst. Phys. (1982)

[10] D.D. Pollock, Thermocouples Theory and Practice, p. 225, CRC press, Boca Raton, Florida, (1991),

[11] University of Cambridge - Department of Materials Science and Metallurgy: Thermoelectric Materials for Thermocouples – Type K Thermocouples: MIMS Configuration, 2009

[12] University of Cambridge - Department of Materials Science and Metallurgy: Thermoelectric Materials for Thermocouples – Type K Thermocouples: Bare wire Configuration, 2009