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PROCESS SIMULATING OF HEAT TRANSFER IN HIGH-TEMPERATURE THERMOCOUPLES

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Abstract. Numerical research of integral characteristics of process of heattransfer in sensitive elements of R, A and B types thermocouples in case of measurement of high temperatures (more than 900 K) is executed. Theoretical dependences of minimum necessary duration of heating up of the thermocouple on value of temperature on boundary of a sensitive element are received. It is shown the thermocouple of R type requires bigger time of heating for obtaining satisfactory accuracy of measurements. Temperature fields in sensitive elements of the specified thermocouples are received. It is shown that distribution of temperature on the thermocouple not linearly and has similar character for the researched thermocouples.

1. Introduction

Thermoelectric effect related with emergence of various thermoelectric phenomena in circuit conductor (Peltier effect, Seebeck effect). Thermoelectric effect gain widespread currency in practice and on its bases design different resources: thermoelectric generators, thermoelectric warmers and coolers and others. Questions about simulations of thermoelectric devices devoted sufficiently large quantity of works (for example, can be distinguish model approximation [2, 3]).

The most widespread example applying effect appearance of EMF in circuit dissimilar conductors provided differences temperatures in places junctions these conductors arise thermoelectric converter (Thermocouple) temperature. Thermocouples are used both in composition of information-measuring systems, well as in composition of control systems, and, hence, reliability their indications effect on directly control of processing procedures. Herewith simulations of thermoelectric converters temperatures from the standpoint of capabilities error estimates and others metrological characteristics paid very few attentions. Such questions considered in [2–6], however at productions problem in works [2, 3] lose sight of features detail of construction thermoelectric converters (considered only direction, corresponding junction of thermocouples).

Engineering design models heat and mass transfer typical thermoelectric converters allows forecast heating period sensors floods thermocouple, necessary for determinations indications to the extent of limits of error.

2. Physical and mathematical model of heat transfer

In present work solve the problem of thermal conductivity for thermocouple, as significantly heterogeneous systems (fig. 1), including thermocouple junction, ceramic nozzle, stainless steel sheath and direction between them, fill out powders of aluminium oxide. Temperature effect of thermocouple wire within the confines of this model ignored.

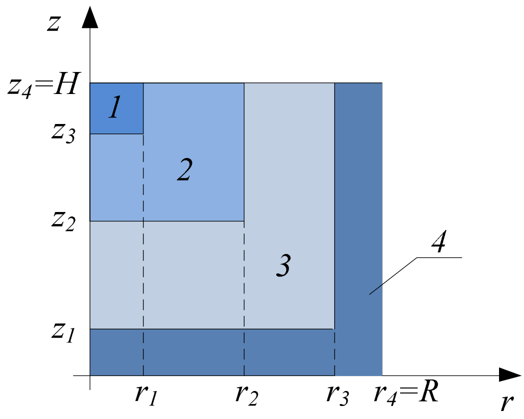

Figure 1. Scheme direction solve the problem: 1– thermocouple junction; 2 – insulating cap; 3 – powder Al_2O_3; 4 – metal cover

Problem of ambulatory heat transfer at the expense of thermal conductivity for elements, incoming direction solve, reduces to solve system of differential equations [7]:

$$c_1 \cdot \rho_1 \cdot \frac{\partial T_1}{\partial t} = \lambda_1 \left(\frac{\partial^2 T_1}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial T_1}{\partial r} + \frac{\partial^2 T_1}{\partial z^2} \right), 0 < r < r_1, z_3 < z < H; \tag{1}$$

$$c_2 \cdot \rho_2 \cdot \frac{\partial T_2}{\partial t} = \lambda_2 \left(\frac{\partial^2 T_2}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial T_2}{\partial r} + \frac{\partial^2 T_2}{\partial z^2} \right), 0 < r < r_2, z_2 < z < z_3; r_1 < r < r_2, z_3 < z < H; \tag{2}$$

$$c_3 \cdot \rho_3 \cdot \frac{\partial T_3}{\partial t} = \lambda_3 \left(\frac{\partial^2 T_3}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial T_3}{\partial r} + \frac{\partial^2 T_3}{\partial z^2} \right), 0 < r < r_3, z_1 < z < z_2; r_2 < r < r_3, z_2 < z < H; \tag{3}$$

$$c_4 \cdot \rho_4 \cdot \frac{\partial T_4}{\partial t} = \lambda_3 \left(\frac{\partial^2 T_4}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial T_4}{\partial r} + \frac{\partial^2 T_4}{\partial z^2} \right), 0 < r < L, 0 < z < z_1; \; r_3 < r < L, z_1 < z < H. \tag{4}$$

The boundary conditions given in table 1.

Table 1 Boundary conditions

$T_1(r_1, z) = T_2(r_1, z)$; $-\lambda_1 \frac{\partial T_1}{\partial r}\Big\vert_{r=r_1} = -\lambda_2 \frac{\partial T_2}{\partial r}\Big\vert_{r=r_1}$	($z_3<z<H$);	$T_1(r, z_3) = T_2(r, z_3)$; $-\lambda_1 \frac{\partial T_1}{\partial z}\Big\vert_{z=z_3} = -\lambda_2 \frac{\partial T_2}{\partial z}\Big\vert_{z=z_3}$	($0<r<r_1$);
$T_2(r_2, z) = T_3(r_2, z)$; $-\lambda_2 \frac{\partial T_2}{\partial r}\Big\vert_{r=r_2} = -\lambda_3 \frac{\partial T_3}{\partial r}\Big\vert_{r=r_2}$	($z_2<z<H$);	$T_2(r, z_2) = T_3(r, z_2)$; $-\lambda_2 \frac{\partial T_2}{\partial z}\Big\vert_{z=z_2} = -\lambda_3 \frac{\partial T_3}{\partial z}\Big\vert_{z=z_2}$	($0<r<r_2$);
$T_3(r_3, z) = T_4(r_3, z)$; $-\lambda_3 \frac{\partial T_3}{\partial r}\Big\vert_{r=r_3} = -\lambda_4 \frac{\partial T_4}{\partial r}\Big\vert_{r=r_3}$	($z_1<z<H$);	$T_3(r, z_1) = T_4(r, z_1)$; $-\lambda_3 \frac{\partial T_3}{\partial z}\Big\vert_{z=z_1} = -\lambda_4 \frac{\partial T_4}{\partial z}\Big\vert_{z=z_1}$	($0<r<r_3$);
$\frac{\partial T}{\partial z} = 0,$	$z=H$	$\frac{\partial T}{\partial r} = 0$	$r=0$
$T = T_r$	$z=0$	$T = T_r$	$r=R$

Here r – radial coordinate, m; z – axial coordinate, m; c – specific heat capacity, J/(kg·°C); ρ – density, kg/m^3; λ – coefficient of heat conduction, W/(m·°C); indexes: 1 – thermocouple junction, 2 – protective cap; 3 – powder of an aluminum oxide, 4 – protective cover.

Solution Procedures

The area of the solution of the task (fig. 1) is broken into the uniform grid consisting of 200 nodes. The slot pitch on radial and axial coordinates is equal $2{,}5\cdot10^{-2}$ mm. The step on a temporal grid changed in the range from 10^{-4} to 10^{-2} with for reduction of volume of computation and increase of accuracy of the decision.

Systems of equations (1)–(4) with the appropriate initial and boundary conditions decided using a method of finite differences. The solution of the difference analogs of the differential equations representing the linear algebraic equations was carried out by a local and one-dimensional method. The pro-race method on the basis of the implicit four-point diagram [8] was applied to the decision of system of the difference equations.

Results and discussion

Computational investigation produced for thermoelectric converter temperature, used for measurement high temperature, with the following nominal static characteristics of conversion: *R*, *A*, *B*.

Mathematical modelling were carried out at parameters [9–11]: thermocouple junction (type *R*): λ_1=49,9 W/(m·K); C_1=139,5 J/(kg·K); ρ_1=20530 kg/m^3; thermocouple junction (type *A*): λ_1=107,5 W/(m·K); C_1=149,1 J/(kg·K); ρ_1=19320,5 kg/m^3; thermocouple junction (type *B*): λ_1=78,17 W/(m·K); C_1=164,17 J/(kg·K); ρ_1=19776 kg/m^3; insulating cap: λ_2=16 W/(m·K); C_2=3480 J/(kg·K); ρ_2=3800 kg/m^3; powder Al_2O_3: λ_3=6,57 W/(m·K); C_3=850 J/(kg·K); ρ_3=1520 kg/m^3; Stainless steel sheath: λ_4=15 W/(m·K); C_4=462 J/(kg·K); ρ_4=7900 kg/m^3.

Measurements of direction solve (fig. 1): H = 5 mm, L = 5 mm.

First part present research aimed at comparative analysis of heat time measuring junction thermocouple to temperature, located within permissible variation from nominal static characteristics of conversion. Permissible variation for research thermocouples in accordance with [12], presented in table 2.

Table 2. Values limits of error measurement temperature of thermocouple

Type thermocouple	Within permissible variation from nominal static characteristics of conversion, K
R	± 1,5 within the limits of temperature from 273 K to 873 K ± 0,004·∣ T – 273 ∣ within the limits of temperature from 648 K to 1273 K
A	± 1,5 within the limits of temperature from 233 K to 648 K; ± 0,004·∣ T – 273 ∣ within the limits of temperature from 648 K to 1273 K
B	± 2,5 within the limits of temperature from 233 K to 573 K; ± 0,0075·∣ T – 273 ∣ within the limits of temperature from 573 K to 1073 K

At solve the problem examined operations of thermocouple, when temperature measuring from 900 K to 1850 K. Chosen within the limits of measurement corresponds range of measurement all thermocouples. Moreover, in chosen within the limits located values of temperatures, considered conversion constant permissible variations of indications thermocouples to linearly dependent from temperature measuring for thermocouples types *A* and *B*. Wherein specified temperatures haves different values for thermocouples types *A* and *B*. Obtained dependences presented at figure 2.

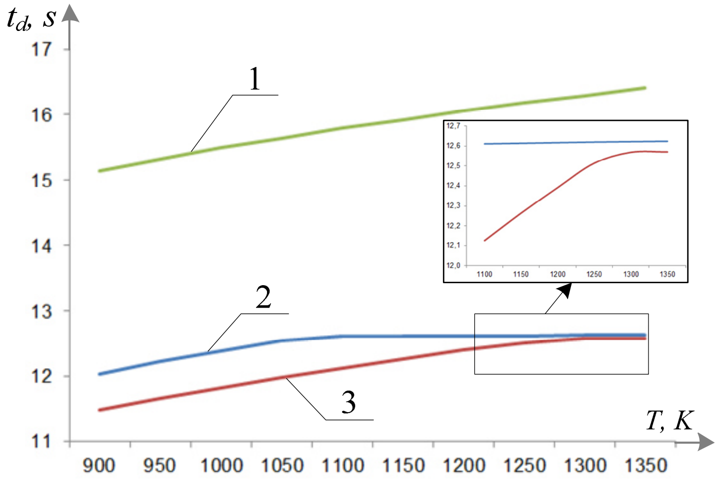

Figure 2. Dependence of heat time sensors from temperature measuring: 1 – thermocouple type *R*; 2 – thermocouple type *B*; 3 – thermocouple type *A*

Based on the results, presented at picture 2, can be next findings:

1) dependence values of heat time sensors thermocouples from temperature measuring is nonlinear character and at direction of temperatures, which corresponding «inconstant» value permissible variation from nominal static characteristics of conversion, tend to «constant» value;

2) heat time sensors thermocouples type *R* at direction of high temperatures (more 1250 *K*) exceeds heat time sensors thermocouples type A and B by a mean of 28,5 %.

The second part of research is connected to determination of influence of duration of heating up on a measurement error of high temperatures the considered thermocouples. The received dependences of the relative error of temperature measurement arising owing to insufficient time of heating for thermocouples of types R, A and B are givenin fig. 3-5.

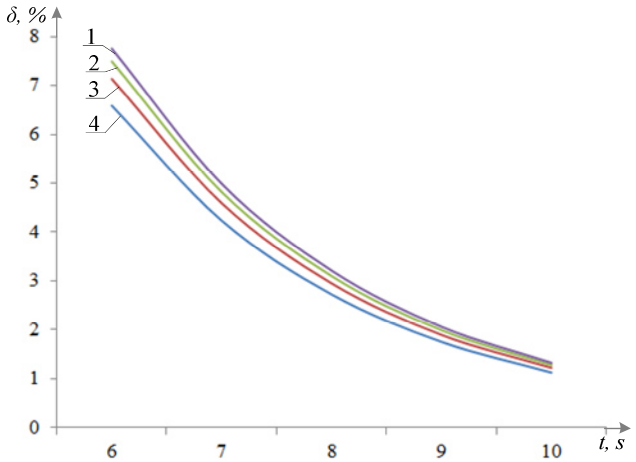

Figure 3. Dependence of the relative error of temperature measurement for the thermocouple of R type: 1 – 1750 K, 2 – 1500 K, 3 – 1250 K, 4 – 1000 K

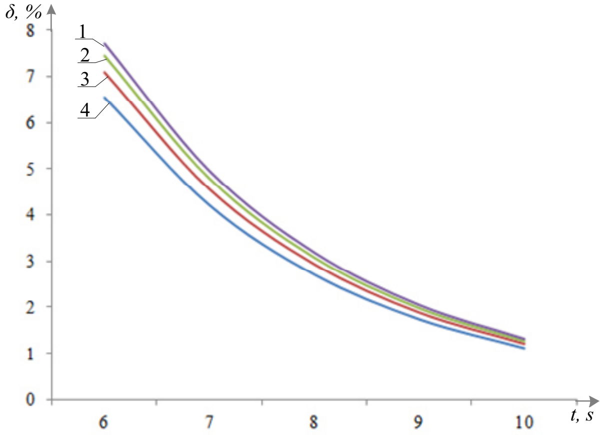

Figure 4. Dependence of the relative error of temperature measurement for the thermocouple of A type: 1 – 1750 K, 2 – 1500 K, 3 – 1250 K, 4 – 1000 K

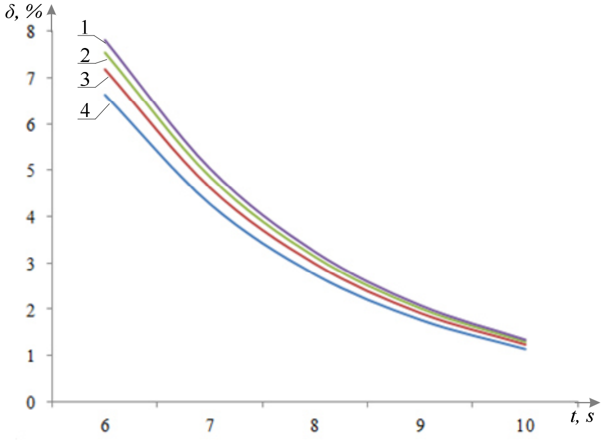

Figure 5. Dependence of the relative error of temperature measurement for the thermocouple of B type: 1 – 1750 K, 2 – 1500 K, 3 – 1250 K, 4 – 1000 K

Follows from the provided dependences that with the sufficient duration of heating up the measurement error can be minimized. Besides, in the range of the taken temperatures from 1000 K to 1750 K value of temperature has no essential impact on a measurement error. Follows from fig. 3-5 that characteristics of process of heattransfer for the considered thermocouples are similar. Distribution of temperature on a sensitive element of the thermocouple of A type (after heating up within 10 seconds) is shown in fig. 6.

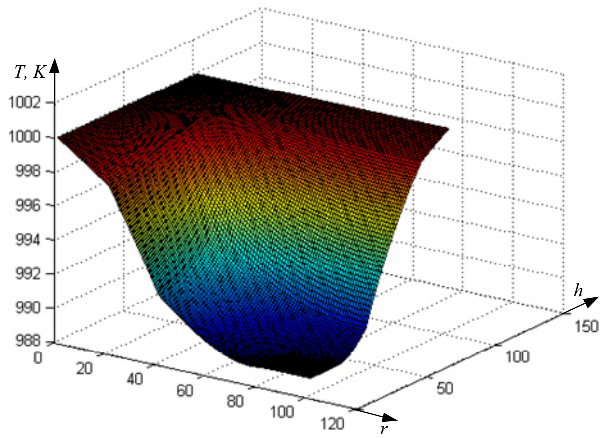

Figure 6. Temperature field in a sensitive element of the thermocouple of A type

Distribution of temperature (fig. 6) not linearly and on axial and radial coordinates has similar character.

Conclusion

The executed numerical researches show that the thermocouple type in case of similar construction of a sensitive element has no impact on heattransfer in case of heating up. The measurement error of high temperatures the considered thermocouples more doesn't depend on the taken temperature and can be lowered at the expense of increase in duration of heating of the thermocouple.

Acknowledgments

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References

1. K. Zabrocki, P.Ziolkowski, T. Dasgupta, J. de Boor, E. Müller. J Electron mater **42**, 7 (2013).
2. Kuznetsov G.V., Mukhammadeev K.M., Engineering Physics, 9 (2009).
3. G.V. Kuznetsov, K.M. Mukhammadeev, Journal of Engineering Thermophysics **19**, 1 (2010).
4. Atroshenko Y. K., Strizhak P. A. and Yashutina O. S. EPJ Web of Conferences **82**, 01061 (2015).
5. Atroshenko Y. K., Strizhak P. A. EPJ Web of Conferences **76**, 01034 (2014).
6. Atroshenko Y. K. , Ozerova I.P., Strizhak P. A. Advanced Materials Research, **1040** (2014).
7. A. Belmiloudi, Heat Transfer. Mathematical Modelling, Numerical Methods and Information Technology, InTech, Rijeka, Croatia, 2011.
8. A. A. Samarskii, The Theory of Difference Schemes, Marcel Dekker, Inc., USA, 2001.
9. Chirkin V.S. Thermal properties of materials: Reference Guide. State Publishing House of physical and mathematical literature, Moscow, 1959.
10. Kinzie P.A. Thermocouple Temperature Measurement. N.-Y., L.: Wiley-Interscience Publ.,1973.
11. R.Hultgren, R.D. Desai, D.T. Hawkins, M.Gleiser, K.K. Kelley. Selected values of the thermodynamic properties of binary alloys, American Society for Metals, 1973.
12. IEC 60584-2. International standard. Thermocouples. Part 2: Tolerances, 1989.