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Determination of necessary time of measurements of surface thermocouples depending on conditions of technological processes

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Abstract. Researches of nonstationary processes of heating up of sensitive elements of thermocouples by means of one-dimensional and two-dimensional mathematical models of heat transfer are conducted. By the created models are defined duration of heating up of the sensitive elements necessary for achievement of the temperature of the thermocouple within a permissible deviation from rated direct current characteristic for three types of thermocouples – K, L and S. Distinctions in the results received by means of one-dimensional and two-dimensional models of heat transfer are shown and justified. For surface thermo-electric transformers, temperature measurement conditions are simulated in case of different value of air gap between the heater and thermocouple surface. It is shown that the value of a gap has an essential impact on minimum necessary time of measurement. Change of duration of heating up of thermocouple from heatphysical characteristics of the typical materials which are used in the case of manufacture of sensing elements is probed.

1. Introduction

Temperature is one of the key parameters characterizing a status of physical entities and processes. Nowadays, temperature measurements are used for control and condition monitoring of technological equipment and quality of technological process behavior in all industries. Such as [1–4] metallurgy, power engineering, aircraft industry, and also medicine, fire safety [5, 6] and other person focus areas are among such productions.

The thermocouples based on usage of the Seebeck effect [7] are the most widespread among the temperature gages implementing a contact method of measurement. Quality of measurement which is provided by the thermocouples, characterized by measuring accuracy and reliability of measuring information, has an essential impact on control performance and quality monitoring of technological process.

The international standard [8] defines eight types of thermocouples. Thermocouples type L were widely adopted in Russia and CIS countries. Thermocouples of the type K and the type E are generally applied in the international practice for measurement of temperatures in the range of $-200\,^{\circ}$C to $+1100\,^{\circ}$C. Application of other types of thermocouples is caused, as a rule, by special conditions and

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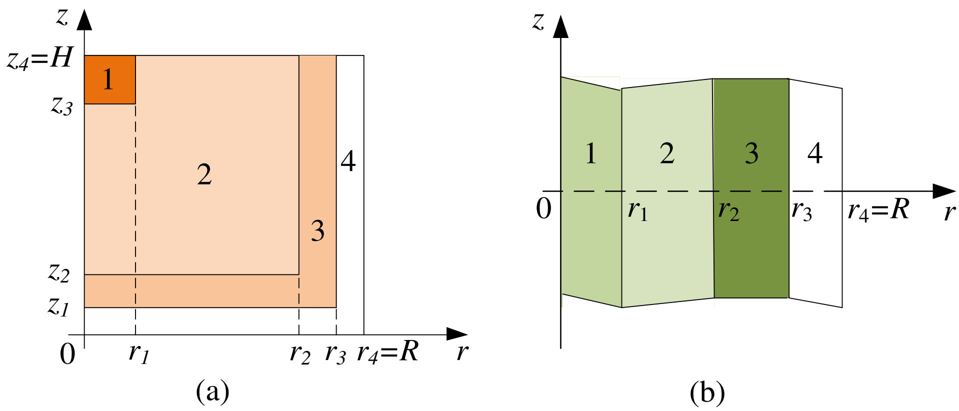

Figure 1. Solution domains of one-dimensional (a) and two-dimensional (b) heat transfer problems: 1 – thermocouple junction, 2 – the powder Al_2O_3, 3 – protector case, 4 – air gap.

the temperature range. In particular, thermocouples of R type or the S type are used as reference one in case of calibration of thermocouple.

Different requirements can be imposed to thermocouples according to an application domain [9]. The main requirement is connected to support of the maximum measurement accuracy. The runtime of measurements plays the important role in case of an error assessment of temperature measurement by thermocouples. As a result, it is expedient to know the necessary time of thermocouple indications establishment, and also the possible influence of external and internal factors at this time when carrying out measurements.

Prediction of thermocouple heating-up time can be executed by numerical simulation of an interdependent processes complex of heat transfer to the neighborhoods of the thermocouple sensitive element. A fairly large number of works (for example, [2, 3, 9–11]) was devoted to the solution of such problems with use of balance approaches and methods. The results of the adjoint heat transfer problem solutions taking into account real operating conditions of thermocouple practically are not present.

The present work is concerned with problems of minimum necessary time prediction for heating up of the thermocouple sensitive elements in different conditions of measurement implementation. The following model of heat transfer was developed for this purpose.

2. Physical model of heat transfer

The "air – protector case – powder – thermocouple junction" system was considered in case of creation of the heat transfer problem solution domain. Geometrical representation of the described non-uniform system constituting the one-dimensional heat conduction problem solution domain is given in Fig. 1b. The two-dimensional heat conduction problem solution domain is provided in Fig. 1a.

The following assumptions were accepted in case of numerical simulation for solution domain given: thermal and physical characteristics of the thermocouple's sensitive element materials, and also thermal and physical characteristics of air don't depend on temperature.

Thermocouple heating up is conducted from the heating surface separated from the thermocouple's sensitive element by air gap 5 (Fig. 1). The initial temperature of the thermocouple's sensitive element is 20 °C. The achievement of thermocouple junction temperature to the values which are in limits of allowed (Table 1) error [12, 13] is the criterion of the heating-up finish of thermocouple.

Diameter of a typical thermocouple's sensitive element is 5 mm. Height of the thermocouple's sensitive element section is restricted by height of 5 mm from the lower bound. Thickness of air gap

Table 1. Dependence of ignition delay time on the metal particle initial temperature.

Thermocouple type	Permissible deviation limit from nominal static characteristics, °C
S (2 tolerance class)	±1.5 in the range of temperatures from 0 to 600 °C
K (1 tolerance class)	±1.5 in the range of temperatures from −40 to 375 °C; ±0.004 · *t* in the range of temperatures from 375 to 1000 °C
L (2 tolerance class)	±2.5 in the range of temperatures from −40 to 300 °C; ±0.0075 · *t* in the range of temperatures from 300 to 800 °C

between a heating element and a sensitive element surface was varied when carrying out the numerical simulation in the range from 1 mm to 10 mm.

3. Mathematical model

The two-dimensional mathematical model of heat transfer process for the thermocouple's sensitive element (Fig. 1a) is described by the system of differential equations in private derivatives:

$$C_1\rho_1\frac{\partial T_1}{\partial t} = \lambda_1\left(\frac{\partial^2 T_1}{\partial r^2} + \frac{1}{r}\frac{\partial T_1}{\partial r} + \frac{\partial^2 T_1}{\partial z^2}\right), \tag{1}$$

$$t > 0,\ 0 < r < r_1,\ z_3 < z < H;$$

$$C_2\rho_2\frac{\partial T_2}{\partial t} = \lambda_2\left(\frac{\partial^2 T_2}{\partial r^2} + \frac{1}{r}\frac{\partial T_2}{\partial r} + \frac{\partial^2 T_2}{\partial z^2}\right), \tag{2}$$

$$t > 0,\ 0 < r < r_2,\ z_2 < z < z_3;$$

$$t > 0,\ r_1 < r < r_2,\ z_3 < z < H;$$

$$C_3\rho_3\frac{\partial T_3}{\partial t} = \lambda_3\left(\frac{\partial^2 T_3}{\partial r^2} + \frac{1}{r}\frac{\partial T_3}{\partial r} + \frac{\partial^2 T_3}{\partial z^2}\right), \tag{3}$$

$$t > 0,\ 0 < r < r_3,\ z_1 < z < z_2;$$

$$t > 0,\ r_2 < r < r_3,\ z_2 < z < H;$$

$$C_4\rho_4\frac{\partial T_4}{\partial t} = \lambda_4\left(\frac{\partial^2 T_4}{\partial r^2} + \frac{1}{r}\frac{\partial T_4}{\partial r} + \frac{\partial^2 T_4}{\partial z^2}\right), \tag{4}$$

$$t > 0,\ 0 < r < L,\ 0 < z < z_1;$$

$$t > 0,\ r_3 < r < r_4,\ z_1 < z < H.$$

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 – powder of an aluminum oxide, 3 –protective cover, 4 – air.

Initial conditions define the temperature distribution in the thermocouple's sensitive element in an initial time point:

$t = 0;\ T = T_0,\ 0 < r < R,\ 0 < z < H,$ where $t_0 = 20\,°\mathrm{C}$ – temperature corresponding to reference conditions.

Boundary conditions of heat transfer problem solution domain are defined as follows.

Boundary conditions of the first kind are set on $r = R$boundary: $r = R$, $T = T_p$, where T_r – temperature of a heating element.

Boundary conditions on $r = 0$ symmetry axis:

$$r = 0,\ \frac{\partial T}{\partial r} = 0 \tag{5}$$

Boundary conditions of the first kind are set on $z = 0$ boundary:

$$z = 0;\ T = T_r \tag{6}$$

Boundary conditions on $z = H$ boundary:

$$z = H;\ \frac{\partial T}{\partial r} = 0. \tag{7}$$

The one-dimensional model is described by similar system of differential equations without heat transfer process along the axis Z direction.

4. Solution method

The given systems of differential equations in private derivatives with the appropriate initial and boundary conditions were solved by the method of finite differences [14]. The solution of the linear algebraic equations representing the difference analogs of differential equations was carried out by a local and one-dimensional method [14]. The sweep method based on the implicit four-point scheme [14, 15] was used to solve the one-dimensional difference equation system.

The problem solution domain was divided into the uniform grid containing 240 nodes with a step of $2.5 \cdot 10^{-2}$ mm on each of coordinates. The non-uniform step on a temporal grid (from 10^{-4} s to 10^{-2} s) was used in order to increase the solution accuracy and reduce the amount of computation.

Results reliability of numerical simulation was estimated according to conservatism verification algorithms of used difference schemes [16–18]. Also the experimental measurements (results are given further) were carried out.

5. Results and discussion

Mathematical modeling were carried out at parameters [19–21]: $\lambda_1 = 33,1$ W/(m·°C), $C_1 = 768$ J/(kg·°C), $\rho_1 = 8825$ kg/m^3; thermocouple junction (type S): $\lambda_1 = 50,4$ W/(m·°C), $C_1 = 139$ J/(kg·°C), $\rho_1 = 20710$ kg/m^3; thermocouple junction (type L) $\lambda_1 = 24,75$ W/(m·°C), $C_1 = 713$ J/(kg·°C), $\rho_1 = 8920$ kg/m^3; powder Al_2O_3: $\lambda_2 = 6,57$ W/(m·°C), $C_2 = 850$ J/(kg·°C), $\rho_2 = 1250$ kg/m^3; protector case steel: $\lambda_3 = 15$ W/(m·°C), $C_3 = 462$ J/(kg·°C), $\rho_3 = 7900$ kg/m^3; air: $\lambda_4 = 0,026$ W/·°, $C_4 = 1190$ J/(kg·°C), $\rho_4 = 1,161$ kg/m^3 [19–21].

The dependences (defined by described models) of sensitive element heating-up (t_d) duration of different thermocouples types (K, L, S) are given in Fig. 2 to illustrate the results of executed investigations of sensitive element heating-up process.

The dependence of minimum necessary duration for thermocouple heating-up has non-linear character for investigating thermocouples. Minor changes of time value of L type thermocouple heating-up for temperature more than 300 °C and for K type – more than 375 °C are caused by the fact that the permissible deviation from the nominal static characteristics for specified thermocouple in case of more high temperatures has not constant character, and depends on the measuring temperature [15].

The results received by means of one-dimensional (Fig. 1b) model, significantly differ from the results defined by means of two-dimensional (Fig. 1a) models. Time values of the thermocouple's sensitive element heating-up, defined on one-dimensional model, exceed the values received by means of two-dimensional model more than by 4 times. It is caused by that such model does not consider the

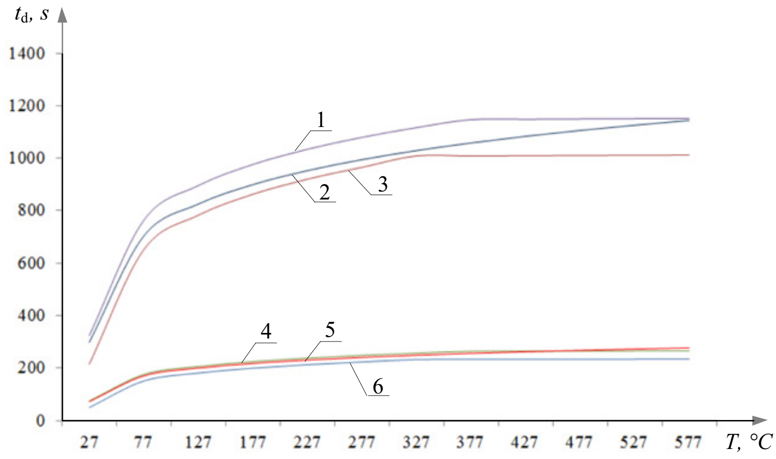

Figure 2. Dependences of heating-up duration of the thermocouple's sensitive elements: one-dimensional model (1: type K, 2: type S, 3: type L); two-dimensional model (4: type K, 5: type S, 6: type L).

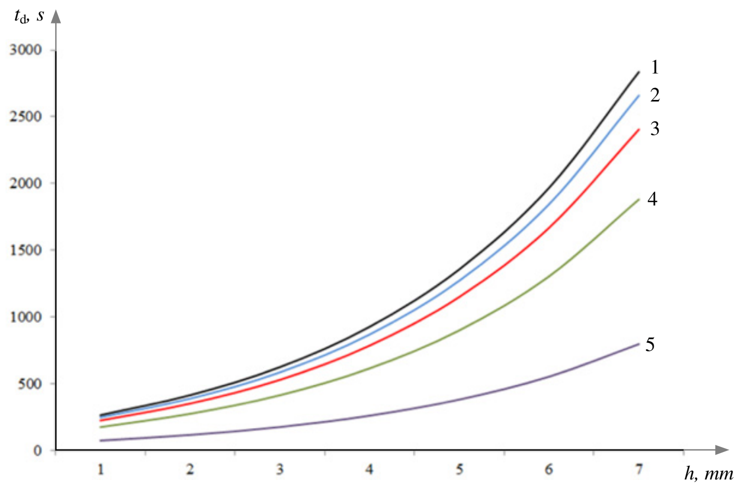

Figure 3. The K type thermocouple sensitive element heating-up duration dependences on value of air gap between a sensitive element and a heating element: 1: T = 577 °C; 2: T = 277 °C; 3: T = 177 °C; 4: T = 77 °C; 5: T = 27 °C.

sensitive element heating-up from lower bound. In this case the one-dimensional model can be used for prediction of heating-up time of thermocouples placed in the furnaces, having rather big length of the heating camera.

Prediction of heating-up time necessary for minimization of an error from "incomplete" thermocouple contact with a heated surface is an important aspect when planning experiment. Theoretically certain dependence by means of numerical simulation for thermocouple K type is given in Fig. 3.

Data retrieveds for thermocouples L and S are similar to the dependences given on Fig. 3. Dependence between value of air gap and thermocouple heating-up time has non-linear character. The air gap thickness increase influences substantially on minimum necessary value of thermocouple heating-up duration. The analysis of a Fig. 3 shows that thermocouple heating-up duration non-compliance will lead to essential increase of temperature determination error in case of metering.

The change of material structure and characteristics – elements of thermocouple's sensitive element (owing to its continuous operation, mechanical damages and other promoting processes) is one of measuring transducers error sources. In particular, the thermocouple continuous operation causes not only the change of thermocouple wire thermo-electric properties, but also can lead to the qualitative composition change of one of thermocouple elements – aluminum oxide powder.

In this work the investigation of powder thermal and physical characteristics change, influence, caused by the change of its qualitative composition, was carried out by "powder – air" ratio change in the field 3 (Fig. 1a) in case of numerical simulation. The specified ratio is characterized by φ powder porosity coefficient. There is no air in the field 3 (Fig. 1a) in case of $\varphi = 1$. The value 0.2 was accepted as minimum φ because in practice of thermocouple maintenance even in case of the long operation terms and mechanical damages the lowering of φ to such values is improbable [1–7].

The thermocouple sensitive element heating-up time decreases by 10–20% in case of deal increase of powder into the field 3 (Fig. 1a). Change of heating-up velocity with the deal increase of powder is carried out under the non-linear law. This result illustrates that thermal and physical characteristics of the filling substance have substantially impacted on thermocouple's sensitive element heating-up time.

Accounting changes of thermal and physical material characteristics – thermocouple's construction elements – will allow lowering the errors connected to the long operational lifetime of measuring transducers when planning and carrying out measurements by means of thermocouples.

6. Conclusions

The heat transfer models, allowing predicting the typical thermocouple's sensitive element heating-up duration, were developed which are necessary to establish the indications of thermocouple within an assumed error. Adequacy of the developed models was confirmed by the experimental data. It was set that value of a gap between the heater and a sensitive element has an essential impact on thermocouple heating-up duration. The inference was drawn that the metering duration plays an important role and substantially promotes the reduction of measurement error in the presence of air gap between the thermometer and the heater. The influence of physical properties change of the main thermocouple components on results of measurements is also revealed.

The developed model allows estimating the result's reliability and believability of temperature measurement (in typical points of a technological path) by thermocouples in their use in actual practice. It is possible to predict the significance and consequences of inaccurate temperature measurements with use of the created models if it will be considered that the thermocouple warm-up up with required values times can reach in several minutes and times of emergency situation development at real productions quite often don't exceed even one minute.

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