JOURNAL OF MECHANICAL AND TRANSPORT ENGINEERING
Vol. 69, No. 3 2017
DOI 10.21008/j.2449-920X.2017.69.3.04

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(Received: 30 JUL 2017, Received in revised form: 11 OCT 2017, Accepted: 13 OCT 2017)

SELECTION OF TEMPERATURE MEASURING POINTS IN A CYLINDER

This paper presents the method of selection of temperature measuring points in a cylinder. Measuring points were selected with regard to technological capabilities of spot drilling and the accuracy of measuring system of the heat-treating furnace VTR PP. Analysis showed where thermocouples should be located so that the heat flow in the heated cylinder was minimally disturbed. Calculation model developed in the FreeFEM++ environment is presented in this paper. It includes unsteady heat conduction equation and depended on temperature heat conduction coefficient as well as specific heat for the material of the cylinder. Finite elements method was used for calculations. This method can be applied for cylinder geometry irrespective of heating parameters and the material the heated element is made of.

Keywords: temperature measurement, heat treatment, direct and inverse problems, radiation

1. INTRODUCTION

A matter of crucial importance for the processes of heat and thermochemical treatment is the distribution of temperature over time on the boundary of the heated element [Małdziński 2002]. Temperature measurement on the boundary is subject to a significant error. Such an error for measurements done by contact sensors for tem-

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peratures of approx. 550 ºC can be of several dozen degrees [Wiśniewski 1983, Taler 1995]. To reduce the error in measurement, pastes of a high thermal conductivity are used on the contact of the body and the sensor [Taler 1995]. Another way to reduce this error is placing the sensor in a groove or soldering it to the surface of the element. Thermocouples are most often soldered with the binding agent to the surface where temperature will be measured. Binding agent consists mainly of silver, copper and zinc [Taler 1995]. Determination of temperature on the boundary is also possible by measuring temperature inside the cylinder and solving the inverse problem [Taler 1995, Ciałkowski 1996, Taler, Duda 2003]. Methods of taking temperature measurements with the use of thermocouples in nuclear and conventional power plants were discussed in paper [Taler 1995]. This paper also presented a case of thermocouples being located in the shields of combustion chambers walls in boilers, where the heat exchange took the form of radiation.

2. SCOPE OF RESEARCH WORK

To determine exactly the distribution of temperature on the surface of the cylinder, one should measure temperature at inner points of the cylinder and solve the inverse problem for the heat conduction equation. Such measurement should be taken as exactly as possible, having regard to furnace measuring system capabilities (accuracy of temperature measurement, accuracy of temperature recording, frequen-

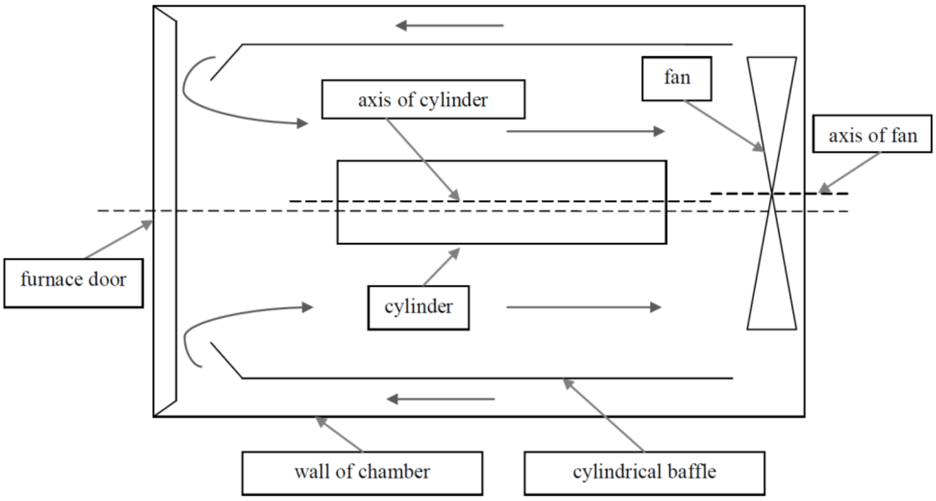


Fig. 1 Schematic diagram of furnace for heat treatment VTR PP

cy of measured data recording). Exact temperature measurement depends on the location and the method of thermocouples installation. This paper includes the analysis of the research work section dedicated to the selection of points where thermocouples would be located.

At the previous stage of the research work [Joachimiak et al. 2016], the cylinder was heated in the cylindrical reversing-chamber furnace (Fig. 1) up to the temperature of 550 ºC. Temperature measurement was performed by eight thermocouples located at depth of 4.5 mm perpendicularly to the cylinder's lateral area (Fig. 2). Thermocouples used in the experiment were of K type, nickel – chromium – nickel. Their diameter was of 1.5 mm. Set heat speed was 5 ºC/min., and fan's rotation speed was 1400 rotations/min. Based on the initial stage of research, planes, where thermocouples would be located, were determined [Joachimiak et al. 2016]. These planes were at the distance of 316.5 mm (plane A-A) and 319.5 mm (plane B-B) from the bottom of the cylinder, on which the gas was flowing in (Fig. 2).

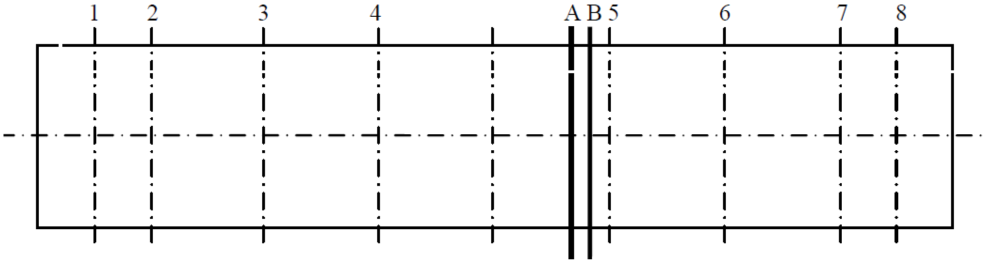


Fig. 2 Location of thermocouples from the initial stage of research work with marked planes in the cylinder

Measurement, obtained in the initial stage of research work, was also used for calculation of the temperature distribution on the boundary of the cylinder. Calculation model, discussed in papers [Joachimiak, Ciałkowski 2014, Joachimiak and Ciałkowski 2015] was applied. It comprised the constant value of the heat conduction coefficient λ and of specific heat c for the whole heating process. Obtained temperature distribution (Fig. 3) was assumed as test distribution for the analysed heating processes.

Due to significant changes of the heat conduction coefficient λ and specific heat c in the temperature interval from 20 to 550 ºC [Incropera, De Witt 1996], for the test temperature distribution on the boundary of the cylinder, calculations in the FreeFEM++ environment were done with regard to a dependence of these parameters on temperature. Temperature distribution inside the cylinder was used for analysis of thermocouples location in the cylinder at the next stage of research work. In this paper, the method of selection of temperature measurement points is described.

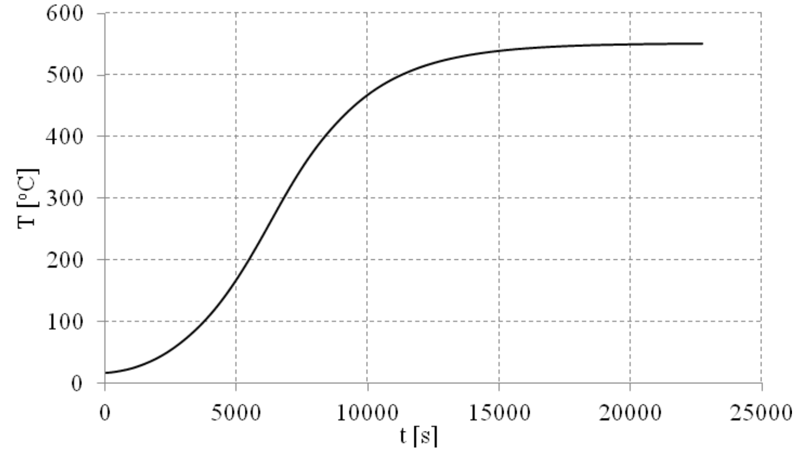


Fig. 3 Test distribution of temperature on the boundary of the cylinder

Experimental results of temperature distribution at these points will be used as input data for the inverse problem. It will enable determining temperature on the boundary of the cylinder for heat treatment process with regard to changes in thermal properties of steel depended on temperature.

3. CALCULATION MODEL

The following heat equation is given inside the cylinder

$$\rho c(T)\frac{\partial T}{\partial t} - div\left(\lambda(T)\nabla T\right) = 0 \tag{1}$$

with the initial condition

$$T\left(r, t=0\right) = T_0 \tag{2}$$

and the boundary condition

$$T\left(r=R, t\right) = T\big|_{\Gamma} = f\left(t\right) \tag{3}$$

Replacing the derivative $\frac{\partial T}{\partial t}$ with the backward difference quotient, we have

$$\rho c\frac{T\left(t_i, x, y\right) - T\left(t_{i-1}, x, y\right)}{\Delta t} - div\left(\lambda \nabla T\left(t_i, x, y\right)\right) = 0 \tag{4}$$

Equation (4) was multiplied by the testing function $w\left(x, y\right)$ and integrated over the region Ω, being the cross-section of the cylinder

$$\int_{\Omega} \rho c \frac{T_i - T_{i-1}}{\Delta t} w \mathrm{d}\Omega - \int_{\Omega} div(\lambda \nabla T_i) w \mathrm{d}\Omega = 0\,,\ T_i = T(t_i, x, y) \tag{5}$$

After applying the Green theorem [Verfürth 2012], the following equation was obtained

$$\int_{\Omega} \rho c \frac{T_i - T_{i-1}}{\Delta t} w \mathrm{d}\Omega - \left(\int_{\Gamma} \lambda \frac{\partial T_i}{\partial n} w \mathrm{d}\Gamma - \int_{\Omega} \lambda \nabla T_i \nabla w \mathrm{d}\Omega \right) = 0 \tag{6}$$

Further in the text we will omit the index “i” standing by temperature T_i. The Dirichlet boundary condition in the form of temperature on the boundary of the cylinder was assumed for calculations. Equation (6) was noted in the FreeFEM++ environment as follows [Hecht et al.]

$$\text{problem thermic}(T, w) = \operatorname{int} 2d(Th)\left(\frac{\rho c T w}{\Delta t} + \lambda \left(\frac{dT}{dx}\frac{dw}{dx} + \frac{dT}{dy}\frac{dw}{dy} \right) \right) -$$

$$- \operatorname{int} 2d(Th)\left(\frac{\rho c T_{old} w}{\Delta t} \right) + on(C, T = f) \tag{7}$$

Calculations were conducted for the cylinder of the radius R = 0.05 m, made of steel of density ρ = 7841 kg/m^3. It was assumed that the initial temperature of the cylinder was T_0 = 16.5 °C, time of heating was t = 22 710 s, and time step was Δt = 30 s. Calculations were conducted for the heat conduction coefficient λ and specific heat c, depended on temperature [Incropera, De Witt 1996], described by a linear combination of Chebyshev polynomials [Paszkowski 1975]:

$$\lambda(T) = \sum_{i=0}^{n} a_i W_i(\tilde{T} \tag{8}$$

$$c(T) = \sum_{i=0}^{n} b_i W_i(\tilde{T} \tag{9}$$

where temperature $\tilde{T}$ $\frac{{}_{\max} - T_0}{T_{\max} - T_0}$, $\tilde{T}$. Coefficients a_i and b_i were determined with the use of least-squares approximation; they are summarized in table 1 [Paszkowski 1975, Incropera, De Witt 1996, Joachimiak 2014]. Application of the heat conduction coefficient and specific heat values depending on temperature are presented in Fig. 4.

Table 1

Coefficients of polynomials approximating functions λ(T) and c(T).

i	a_i	b_i
0	41,519	660,92
1	-11,350	247,36
2	-0,90257	51,725
3	0,010553	18,980

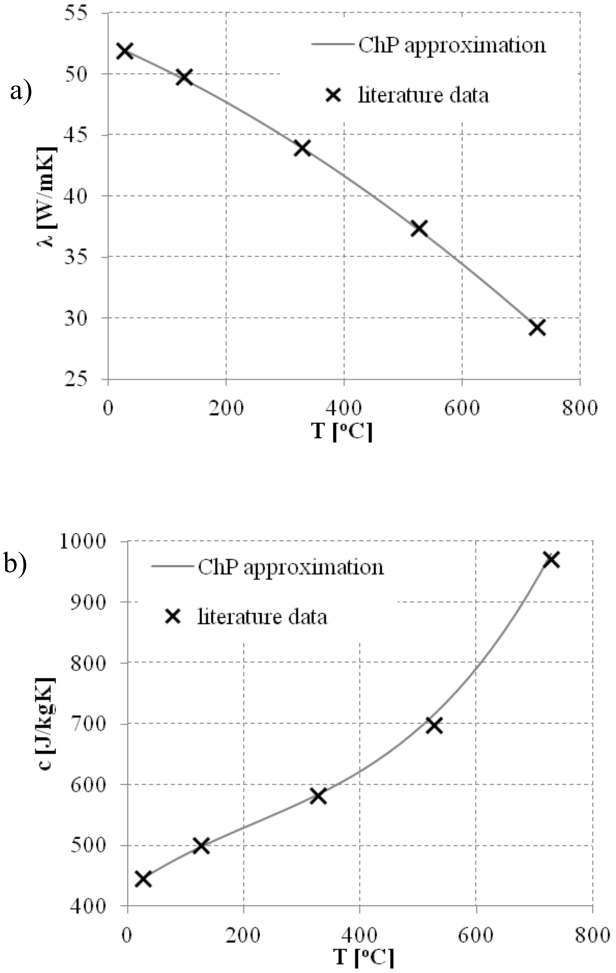


Fig. 4. Application of heat conduction coefficient value (a) and specific heat value (b) for calculations, depending on temperature, obtained from literature data and from the approximation by the Chebyshev polynomials

Calculation were made in the Cartesian system for a triangle mesh with the Lagrange P1-type interpolation (continuous, piecewise-linear) of temperature in the mesh element. Calculations were made twice for grids consisting of 100 and 400 elements on the circle perimeter (Fig. 5). Obtained results differed slightly. To obtain good accuracy of calculations results for each time step, we did five-time iteration of temperature distribution with regard to the variability of λ(T) and c(T).

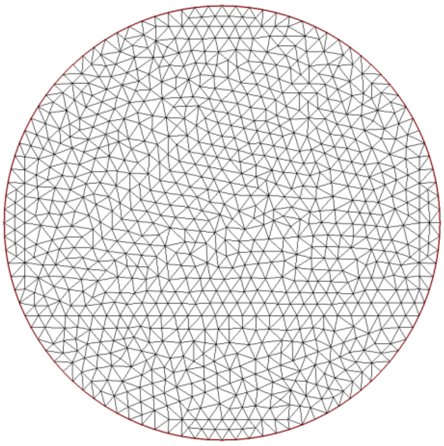
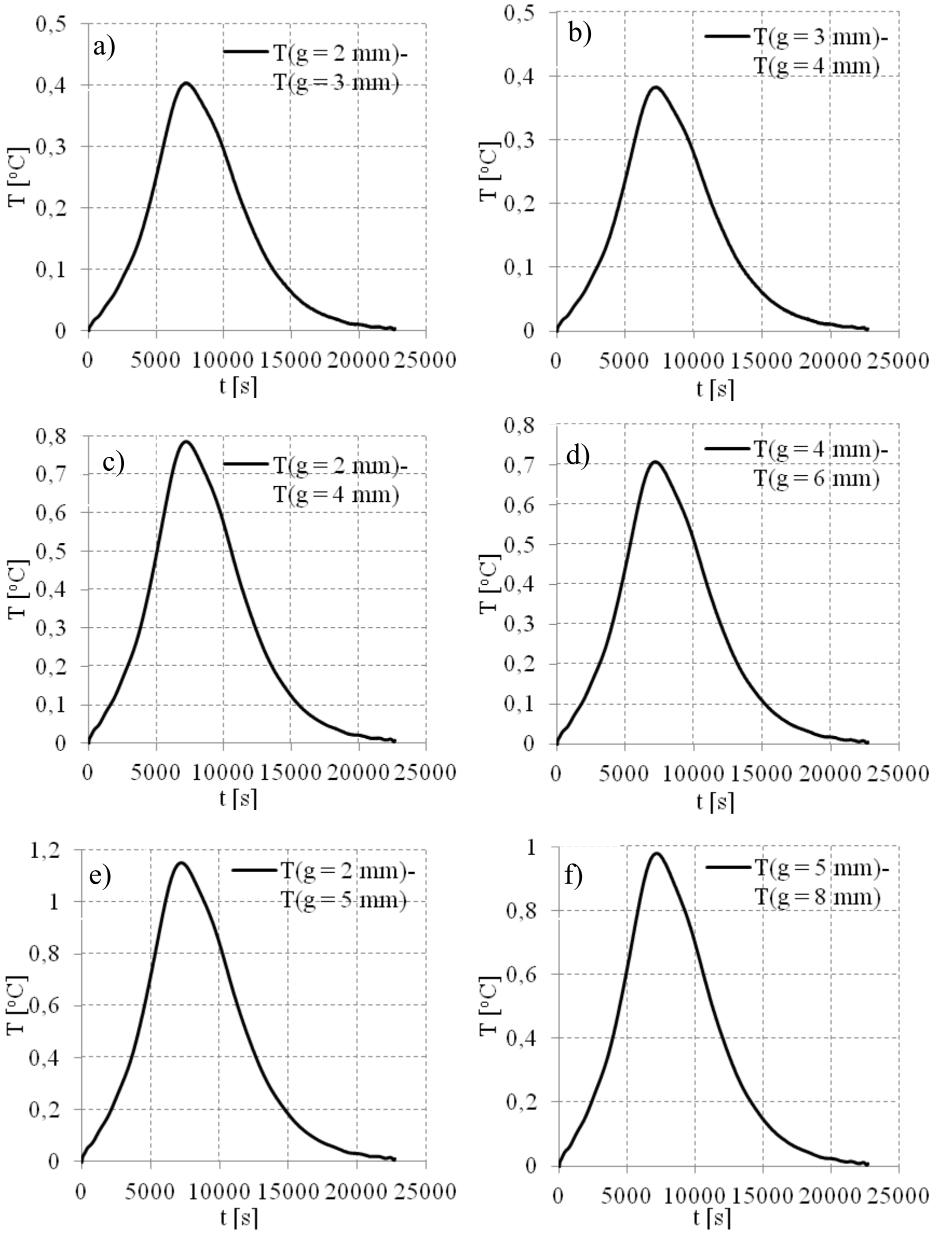


Fig. 5. Grid for calculations in FreeFEM++ software consisting of 100 elements on the circle perimeter

4. RESULTS OF CALCULATIONS

To select measuring points, differences in temperature in points located at the distance of 2 and 3 mm (Fig. 6a), 3 and 4 mm (Fig. 6b), 2 and 4 mm (Fig. 6c), 4 and 6 mm (Fig. 6d), 2 and 5 mm (Fig. 6e), 5 and 8 mm (Fig. 6f), 2 and 6 mm (Fig. 6g) as well as 6 and 10 mm (Fig. 6h) from the boundary were determined. Minimal differences in temperature were obtained for thermocouples located 3 and 4 mm from the boundary and they varied from 0 °C to 0.4 °C (Fig. 6b). Accuracy of the furnace measuring system was 0.1 °C. For considerable part of measurement time these differences would be readable for the measuring system. Due to planned solution of the inverse problem with the use of measurement data, it was advantageous to locate thermocouples as close to the boundary as possible. For technical reasons it was possible to made a hole located at the closest distance from the boundary of the cylinder which axis is distant by 2 mm from the boundary. Therefore, it was decided to drill holes at distances of 2, 3 and 4 mm from the boundary. Since of great importance is the measurement taken at the distance of 2 mm from the boundary, two holes for such measurements were drilled. Due to the measuring stand structure we were able to install six thermocouples. Other two thermocouples were located at the distances of 6 and 8 mm from the cylinder boundary. It would enable recording temperature in four equidistant points located at the distance of 2, 4, 6 and 8 mm from the boundary. Thermocouples located 6 and 8 mm from the boundary would enable observation of temperature differences in the cylinder cross-section at the beginning and at the end stage of heating process, when temperatures in the cylinder are most balanced.


a)
T(g = 2 mm)-
T(g = 3 mm)
b)
T(g = 3 mm)-
T(g = 4 mm)
c)
T(g = 2 mm)-
T(g = 4 mm)
d)
T(g = 4 mm)-
T(g = 6 mm)
e)
T(g = 2 mm)-
T(g = 5 mm)
f)
T(g = 5 mm)-
T(g = 8 mm)
T [°C]
t [s]
0
5000
10000
15000
20000
25000
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
1
1,2

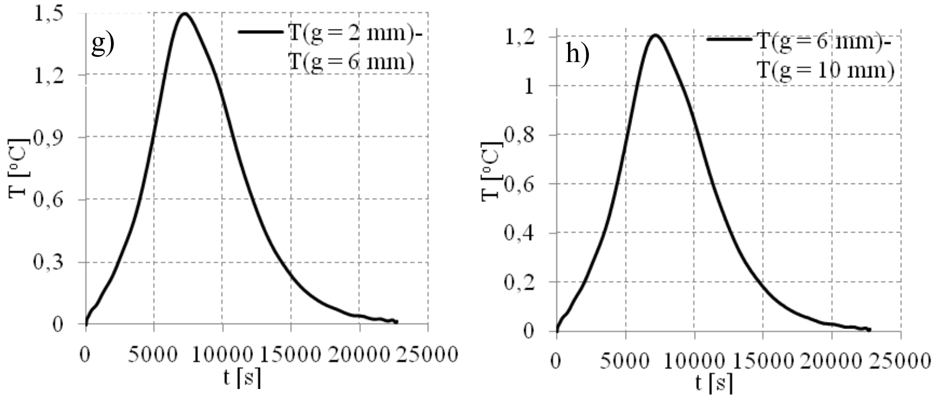


Fig. 6. Differences in temperatures for thermocouples at distances of: a) 2 and 3 mm, b) 3 and 4 mm, c) 2 and 4 mm, d) 4 and 6 mm, e) 2 and 5 mm, f) 5 and 8 mm, g) 2 and 6 mm, h) 6 and 10 mm from the boundary

5. METHOD OF DRILLING

Temperature measurement in each selected point is related to drilling a hole which ended in the selected temperature measurement place. To take a precise measurement, six selected measuring points should be located within the isothermal region along the cylinder. This region was determined with regard to heat flow into the axial direction [Joachimiak et al. 2016]. Measurement taken by any thermocouple should not be disturbed by other holes. Heat was flowing into the radial direction. It meant that on the radius running through the measuring point there should not be other holes which could disturb the flow. This guaranteed the continuity of material on the way of heat conduction. Cylinder was heated on its perimeter in the furnace, therefore such heating could be assumed as the even one. It resulted from the construction of the furnace. Hence, irrespective of the angle, we had similar temperature on the same radius of the cylinder. It could be assumed that points on the same radius were on the isothermal surface.

Holes should be drilled in such a way that they are tangential to isotherms on the cylinder cross-section (Fig. 7). Then, the thermocouple is located perpendicularly to the radius running through the measuring point. Taking the above assumptions into account, six holes were drilled. They were located in two planes at the distances of 316.5 mm (plane A-A) and 319.5 mm (plane B-B) from the bottom of the cylinder on which the gas was flowing in. Selection of thermocouples distances from the boundary was also considered. In the plane A-A, thermocouples were located at the distance g = 2, 3 and 4 mm from the boundary. Holes were drilled under the angle of 30°, 180° and 330°. In the plane B-B, holes were located at the distance g = 2, 6 and

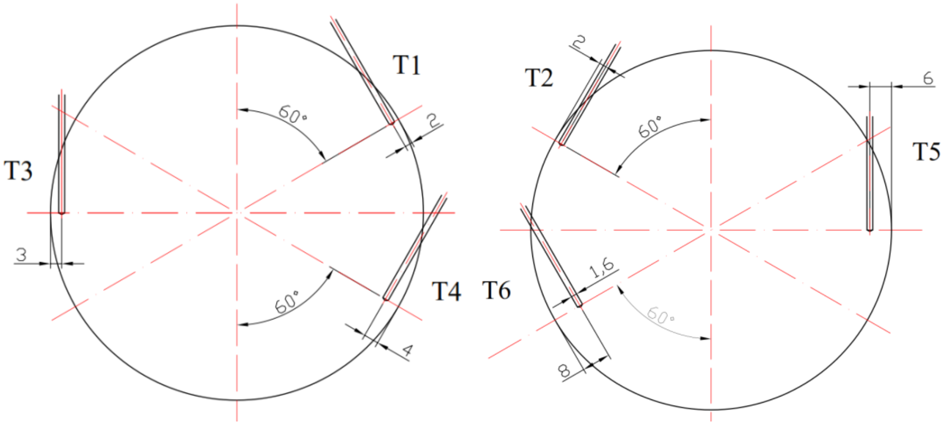


Fig. 7. Schematic picture of drillings for thermocouples in cross-sections: a) plane A-A, b) plane B-B

8 mm from the boundary. Drillings were made under the angle of 0°, 150° and 210°. Each of measuring points was located in the midway of the chord created by the hole's axis (Fig. 6). Angles of holes were selected in such a way that the heat flow would not be disturbed significantly and that thermocouples would not slip out from the holes when the gravitation and vibrations generated by the fan impacted on them.

6. VERIFICATION OF DRILLINGS CORRECTNESS

After drillings had been done, each hole was measured and it occurred that holes for thermocouples T3 and T6 were drilled incorrectly (i.e. the position of temperature measurement is not in the assumed point). By contrast, holes for thermocouples T2, T4 and T5 were drilled correctly. Hole for thermocouple T1 was made correctly, that is along the isotherm, but it was located at the distance of 1.9 mm from the boundary. In further stage of research work measurements taken with the use of thermocouples T1, T2, T4 and T5 were considered. Figure 8 presents selected results of measurements for time of approx. 6000 s. Obtained temperature values for heating processes should be the highest for thermocouple T1, being the closest to the boundary of the cylinder, and should gradually decrease for subsequent thermocouples from T2, T4 to T5. Figure 8 shows that this sequence is maintained. Thermocouples T1, T2, T4 and T5 show one by one decreasing temperature. Analogous dependences were examined for other heating processes and were observed for other time units. Differences in temperature in the selected measuring points are noticeable by the measuring system what proves the correctness of points selection.

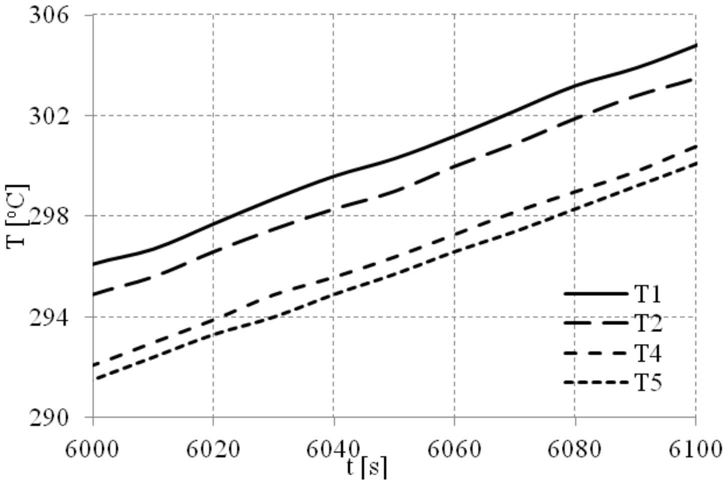


Fig. 8. Results of temperature measurements for time from the interval 6 000-6 100 s [Joachimiak 2014]

7. SUMMARY

Selection of temperature measuring points in the cylinder for nitration processes was described in this paper. The method of selection of the location for thermocouples can be applied for cylindrical geometries for any heating parameters. Verifying temperature measurement indicated that the selection of measuring points was done properly. In the next stage of research work a precise determination of temperature distribution on the boundary of the cylinder will be done for various speeds of charge in the heat-treating furnace heating. The aim of further stage of research work is to measure temperature inside the heating cylinder at selected points and to solve the non-linear inverse problem including the change of the cylinder material parameters depending on the change in temperature.

NOMENCLATURE

c	specific heat [J/kgK]
div	divergence
f	temperature on the boundary of the cylinder
g	distance of the thermocouple from the boundary of the cylinder [m]
r	radius [m]

t	time [s]
T	temperature [^{o}C]
Th	calculation domain
w	testing function
W_i	Chebyshev polynomial of i-th degree

Greek symbols:

λ	heat conduction coefficient for the cylinder, W/mK
ρ	density, kg/m^3
Ω	region of integration

Subscript:

0	initial time, for $t = 0$
i	in i-th time unit
max	(value) maximal during heating
old	in previous time moment
Γ	outer region of the cylinder

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ACKNOWLEDGEMENTS

Działalność statutowa 05/56/DSMK/4948.

DOBÓR PUNKTÓW POMIARU TEMPERATURY W WALCU

Streszczenie

W pracy przedstawiono metodę doboru punktów pomiaru temperatury w walcu. Punkty pomiaru temperatury dobrano z uwzględnieniem możliwości technologicznych wykonania nawierceń oraz dokładności układu pomiarowego pieca do obróbki cieplnej VTR PP. Przeprowadzona analiza pozwala na umieszczenie termoelementów w sposób jak najmniej zaburzający przepływ ciepła w nagrzewanym walcu. W pracy przedstawiono model obliczeniowy opracowany w środowisku FreeFEM++. Uwzględniono w nim niestacjonarne równanie przewodnictwa ciepła oraz zależny od temperatury współczynnik przewodzenia ciepła i ciepło właściwe dla materiału walca. W przeprowadzonych obliczeniach posłużono się metodą elementów skończonych. Metoda ta może być stosowana dla geometrii walcowych niezależnie od parametrów nagrzewania i materiału nagrzewanego elementu

Słowa kluczowe: pomiar temperatury, obróbka cieplna, zagadnienie proste i odwrotne, promieniowanie