HEAT SOURCE DESCRIPTION OF ISO–EXOTHERMIC SLEEVES WITH THE USE OF CONTINUOUS FUNCTION

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SUMMARY

The present study was aimed at investigating identification of real thermophysical parameters of insulating–exothermic materials used as riser sleeves. The experiments with steel poured into the moulds containing various insulating and exothermic sleeves were carried out using thermocouples measurement systems (thermal analysis). Then thermal coefficients of these materials were calculated using inverse problem solution. A time–dependent formula of exothermic reaction heat (in W/m³) was called a heat source function. The paper presents a proposed form of the heat source function, providing its justification and the results of tests obtained with its application. For purposes of the study the Calcosoft Inverse Solution system was used.

1. INTRODUCTION

The works [1,2,5] propose a method of determining thermophysical parameters of insulating–exothermic and exothermic sleeves, with consideration of a simplified form of the heat source function, related to the heat liberated in result of exothermic reaction occurring in the sleeve material. It was shown that the best correlation of simulation results and the experiment was achieved with assumption of the heat source function of varying intensity during the process. Another form of the heat source function is proposed in the paper, with its justification. Application of experimental–simulation methods described, among others, in [3], allowed to determine average values of substitute thermophysical coefficients (λ - thermal conductivity, c – specific heat, ρ - density) and the parameters of heat source

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function of the exothermic material. Appropriate calculation has been carried out with the use of the Calcosoft simulation system and its inverse solution module.

2. PROBLEM DESCRIPTION AND METHODS OF ITS SOLVING

Degree of advancement of the chemical reaction, inclusive of exothermic one, is witnessed by the quantity (concentration) of a selected substrate. The rate of any chemical reaction with respect to a given substrate is defined as the rate of concentration decrease \( c \) of the substrate in the time

\[
V = -\frac{dc}{dt}
\]

During the reaction some factors may arise, that should be considered as disturbance – e.g. unsuitable temperature, oxygen deficit, the lack of catalyst. In the simplest case, including analysis of only one substrate (the progress of the reaction depends on its concentration) the reaction rate is proportional to decreasing concentration of the substrate. The time pattern of the reaction rate is determined by solving the following differential equation [4].

\[
V = -\frac{dc}{dt} = k \cdot c^n
\]

In this equation \( n \) stands for reaction order, \( k \) is the coefficient of proportionality. The reaction order may also be fractional. If \( n=0 \) (zero-order reaction), the reaction rate is determined in the process independent on the concentration. Solution of the above differential equation for the first–order reaction gives the time pattern of the reaction rate expressed by a function of exponential type

\[
V = kA\exp(-kt)
\]

where \( A \) is the constant resulting from integral calculation of equation (2)

As it was previously mentioned, the progress of any chemical reaction is determined by the quantity (concentration) of one of substrates of the reaction – in this case it will be the deficit of the \( \text{exo} \)-material in the process of its burning out. The reaction progress will affect the quantity of released heat, being proportional to the rate of the \( \text{exo} \)-substrate decrement. This allowed to adopt the following form of the function of the heat source released in result of the exothermic reaction:
\[ P(t) = Q \exp\left(\frac{-t}{\tau}\right) \]  

where \( t \) is the time elapsed from ignition moment in given location of the sleeve (that is from reaching the ignition temperature, i.e. initiation of an exothermic reaction), \( \tau \) - the value of a time–constant in the mathematical formulation of the exothermic reaction, while \( P(t) \) is thermal power per unit volume of the sleeve. Once the sleeve is poured with liquid metal, its successive layers reach the ignition temperature in result of the heat transferred from the casting.

3. CONSEQUENCES RESULTING FROM THE ASSUMPTION OF EXPONENTIAL PATTERN OF THE HEAT SOURCE FUNCTION

Assumption of the heat source function in the form of the formula (4) is conducive to the following consequences:

1. Total heat quantity released from unit volume of the sleeve (\( Q_{\text{fgz}} \)) shall be expressed as a product of \( Q \) and \( \tau \) coefficients. In order to prove it, the heat source function should be integrated in time.

\[
Q_{\text{fgz}} = \int_0^\infty P(t)dt = \int_0^\infty Q \exp\left(\frac{-t}{\tau}\right)dt = Q \cdot \tau
\]

(5)

2. Quantity of the heat released from unit volume within the time from ignition is expressed by the following function

\[
Q(t) = \int_0^t P(t)dt = \int_0^t Q \exp\left(\frac{-t}{\tau}\right)dt = -Q \tau \exp\left(\frac{-t}{\tau}\right) + Q \tau = Q \tau \left(1 - \exp\left(\frac{-t}{\tau}\right)\right)
\]

(6)

4. THE EXPERIMENT AND SIMULATION COMPUTATION

4.1. Experimental tests

Six steel cylinder castings of the dimensions \( \phi 175 \times 900 \) mm have been made in a single multi-cavity mould. Each of the castings was lagged with another type of material subject to the test. One of them, considered as a reference sample, has been made in quartz sand bonded by furan resin. The other five castings were designed for testing insulation and iso–exothermic materials. These materials, of average thickness amounting to 25 mm, were derived from delivered riser sleeves. Surrounding of the tested sleeves, i.e. the respective part of the mould, was made of furan sand. Each cavity of the mould contained two PtRh-Pt thermocouples, one of them being located in the
casting axis, the other at the depth of 30mm, counting from interface casting–mould. An important location suitable for the measurement was a background of the tested coating (sleeve). Two K-type thermocouples were located at each of the sleeve–mould sand interfaces. An example of instrumentation of a selected cavity and the whole mould during the knocking-out operation, as well as the thermocouples, are shown in Figure 1.

The experiment was designed to record the temperature patterns in the castings and mould (cooling and heating curves have been recorded) during the casting and solidification processes. The cooling curves and their derivatives served for determining solidification times of the castings.

Temperatures recorded, and processed into suitable data files, served as experimental data input to the inverse computation system (Calcosoft 2D) in order to determine the average thermal conductivity ($\lambda$), average volumetric specific heat ($C_p$), and the pattern of heat source function during the exothermic reaction of the tested insulation-exothermic and exothermic material.

4.2. Simulation studies

All the tested sleeves have been analyzed. The work provides the results of research of two types of insulation-exothermic materials, denoted as L2 and L5.

In the inverse calculation, performed by means of the Calcosoft 2D Simulation System, such values of the Q parameters have been sought (i.e. initial source power falling at unit volume) and $\tau$ (the time–constant from the relationship [4]) that ensured good compliance of the temperatures $T=T(t)$ recorded during the experiment and the ones obtained in result of simulation of the experiment. The result was assessed each time on the grounds of approximation residuals obtained with the help of the Calcosoft System. The algorithm consisted in iterative searching of the best values of volumetric
specific heat and thermal conductivity of the sleeve for consecutive pairs of the values $Q$ and $\tau$ (parameters of the heat source function), by solving an inverse problem. Finally, thermophysical parameters of the sleeve determined this way were the effect of the simulation process in which the characteristics $T=T(f)$ from the experiment and from the simulation has the best correlation (having the least residual). Such a method allowed simultaneously to carry out the energetic and temperature validation [3].

For purposes of the studies a relatively low ignition temperature, amounting to 150°C, has been assumed that was determined from the analysis of heating curves recorded during the experiment.

The obtained results of inverse solution for the sleeves marked as L2 and L5 are shown in Figures 3 and 4.

![Fig. 2. Comparison of experimental and simulation results of the L2 sleeve](image)

Rys. 2. Porównanie wyników symulacji i eksperymentu dla otuliny L2
5. SUMMARY

Assumption of exponentially decreasing heat source function in description of the heat released from the tested sleeves gives very good correlation between the characteristics obtained from the simulation and temperatures recorded during the experimental test. The calculation allowed determines the total heat of the exothermic reaction for the tested sleeves. For the L2 sleeve it amounts to 2257 [KJ/kg], and for the L5 1857 [KJ/kg]. All the thermophysical coefficients determined for the tested sleeves are specified in Table 1.

It should be noticed that a very important problem solved in this work was original instrumentation of the mould with the thermocouples located in high-temperature environment of casted steel and, in still higher, in the focus of exothermic reaction within the sleeve. Direct measurement of the temperature is practically impossible (it may exceed 2000°C), therefore, the authors desisted from measuring it in the sleeve. After all, the measurement made in the sleeve background provided good repeatability of thermal analysis results of the casting – mould system. This is a necessary condition for the iteration algorithm of inverse tasks to be convergent. The results obtained this way prove full success of the experiment.
Table 1. Specification of the simulation results
Tabela 1. Zestawienie wyników symulacji

<table>
<thead>
<tr>
<th>Otulina</th>
<th>$c_p \times 10^6$ [J/m$^3$K]</th>
<th>$\lambda$ [W/mK]</th>
<th>$T_z$ [°C]</th>
<th>$A$ [W/m$^3$]</th>
<th>$\tau$ [s]</th>
<th>$Q_{egz}$ [KJ/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L2</td>
<td>0.56</td>
<td>1.09</td>
<td>150</td>
<td>0.45*10$^6$</td>
<td>3500</td>
<td>2257</td>
</tr>
<tr>
<td>L5</td>
<td>0.50</td>
<td>0.98</td>
<td>150</td>
<td>1.00*10$^6$</td>
<td>1300</td>
<td>1857</td>
</tr>
</tbody>
</table>

REFERENCES


OPIS ŹRÓDŁA CIEPŁA W OTULINACH ZAWIERAJĄCYCH MATERIAŁ EGZOTERMICZNY ZA POMOCĄ FUNKCJI CIĄGLEJ

STRESZCZENIE

Celem badań była identyfikacja rzeczywistych parametrów termofizycznych materiałów izolacyjno-egzotermicznych występujących w postaci otulin do nadlewów. Przeprowadzono eksperymenty odlewania staliwa do formy, w której zastosowano otuliny wykonane z różnych materiałów izolacyjno–egzotermicznych i umieszczono system termoelementów w celu przeprowadzenia analizy termicznej. Następnie wyznaczono współczynniki termofizyczne tych materiałów stosując metodę obliczeń odwrotnych. Wyznaczaną zależność wydzielającego się ciepła reakcji egzotermicznej (w W/m$^3$) od czasu nazwano funkcją źródła ciepła. Artykuł przedstawia zaproponowaną postać funkcji źródła ciepła oraz jej uzasadnienie, a także uzyskane wyniki badań z jej zastosowaniem. Do obliczeń wykorzystano system symulacyjny Calcosoft.

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