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Mathematical Modeling of Cooling High-Temperature Cylindrical Workpieces

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Abstract

The paper presents the results of modeling the process of cooling a cylindrical metal workpiece made of structural steel by a flowing cooling medium. The authors give a mathematical description of their solution for the problem of convective heat exchange that occurs when a longitudinal water flow is used for cooling. The control volume approach has been used for solving the systems of equations. The parameters of the flow field are calculated by the SIMPLE algorithm. The mathematical model factors in the presence of vapor being generated at the boundary between the high-temperature workpiece and the cooling water flow. It uses the effective vapor volume fraction calculated according to the heat-balance equation. The calculation results obtained by using the proposed model are compared to calculations by a mathematical model that uses criterial equations for determining the boundary conditions on the surface of a high-temperature cylindrical work piece in contact with the water flow. The authors discuss cases of cooling metal workpieces with different initial heating temperatures. The results of the numerical calculations of the heat exchange parameters are analyzed with regard to the time of the cooling process as well as in regard to whether the vapor presence on the cylinder surface is or is not taken into account.

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Keywords: mathematical model; cooling; cylindrical metal work piece; heat exchange parameters; longitudinal flow; numerical calculation;

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Nomenclature

c - specific heat, J/(kg · K)
ρ - density, kg/m^3
λ - heat-transfer capacity, W(m·deg.)
μ - dynamic viscosity, Pa·c
$\dot{m}$ - specific mass rate of evaporation, kg/(m^3·s)
Q - specific heat of evaporation, J/kg
Y - volume concentration of vapor
p - pressure, Pa
T - temperature, °K
t - time, s
x - longitudinal coordinate, m
r - radial coordinate, m
u - velocity component along x, m/s
v - velocity component along r, m/s
$\left\{\bar{\rho},\bar{c},\bar{\lambda},\bar{\mu}\right\} = f\left(Y\right)$

1. Introduction

In mechanical engineering, when metal work pieces such as pipes, shafts, pins, bolts, springs, etc. are made, effective thermal treatment methods for hardening are used. In [1-5], the results of the investigations allowing the improvement of the physical-mechanical properties of metal work piece material and significant decrease of metal consumption were presented. In the Institute of Mechanics UrO RAN, a method was developed for making cylindrical metal work pieces for critical parts from structural steels with the outer diameter in the range of 0.012 – 0.06 m (Fig. 1) [3]. The procedure for hardening metal work pieces was completed with cooling at a preset rate to form desired physical-mechanical properties of a material.

Fig. 1. Cylindrical work pieces

For cooling cylindrical metal work pieces, sprayers are widely used [6-8] allowing creating similar cooling conditions along the metal work piece perimeter due to the uniform and symmetrical supply of a cooling medium in the form of rapidly moving continuous flows of a liquid.

In [9], the problem of cooling a high-temperature solid metal cylindrical work piece with flows of water and air was solved numerically. The cooling liquid flows were considered quasi-stationary. The test calculations confirmed the adequacy of the model construction and the validity of the investigation results. The results of the mathematical modeling of cooling during hardening axisymmetric steel work pieces with quasi-stationary flows of a cooling medium were presented in [10]. In [11], the case was considered when a non-stationary one-dimensional water flow moved along the surface of a high-temperature cylindrical body in the longitudinal axis direction.

A mathematical model was presented in [12] describing cooling a hollow cylindrical metal work piece with longitudinal quasi-stationary water flows. The algorithm of the numerical solution of the problem and the results of the calculation of the parameters of the heat exchange of the cylinder and cooling medium flows were given. The determination of the temperatures of the cooled cylinder was conducted taking into account the time of the relaxation of thermal stresses and internal heat sources caused by polymorphic transformations. The results of the calculation of the parameters of the heat exchange of the cylinder and cooling medium flow depending on the geometry, thermophysical properties and the time of the process were received both in [12] and in [13-17] on the basis of criterial dependences for the determination of the heat exchange conditions.

In the experimental work [18] and the work [19] devoted to numerical solutions, special attention was paid to the investigation of the evaporation of two-phase thin films in the narrow range of heat parameters without taking into account the simultaneous movement of generated vapor and the main flow of liquid. In [20, 21], the mechanism of the vapor generation and the behavior of formed vapor bubbles in the liquid at rest were investigated.

The present work is devoted to the construction of a mathematical model describing cooling heated cylindrical bodies with a non-stationary water flow in two dimensions and the parametric investigation of the process under consideration

2. Mathematical model

A high-temperature solid metal cylinder of radius r_m and length L is cooled with a water flow moving longitudinally in the direction of the axis x and having the initial rate u_0 and temperature T_{0l}. The water thickness is $r_l - r_m$. Above the water layer there is a layer of air with thickness $r_a - r_l$. The physical diagram of the calculation region is presented in Fig. 2.

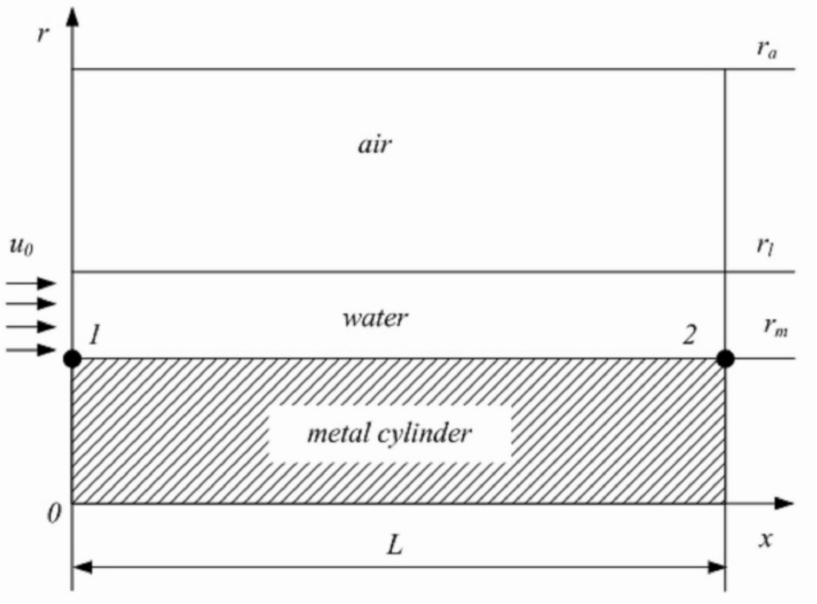

Fig. 2. The physical diagram of the calculation region

At the development of the mathematical model, the following assumptions have been made:

- The air and water flows are considered laminar and axisymmetric relative to the longitudinal cylinder axis.

- The parameters in the direction r are varying continuously; at the 'water-air' boundary, the conditions of the conjugation of the rate and heat parameters are fulfilled.
- In the water near the cylinder surface, the process of the vapor formation takes place.
- Vapor is considered saturated and is described by the gas equation; the vapor density is significantly lower than that of the water.
- The evaporation is assumed equilibrium; the vapor pressure is uniform throughout the bulk and equal to the pressure of the liquid.
- The air is described by the gas equation.

The system of equations for the gas-liquid medium $r_m < r < r_a$ (Fig. 2) has the form.

$$\bar{\rho}\frac{\partial u}{\partial t}+\bar{\rho}u\frac{\partial u}{\partial x}+\bar{\rho}v\frac{\partial u}{\partial r}=-\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\bar{\mu}\frac{\partial u}{\partial x}+\frac{1}{r}\frac{\partial}{\partial r}r\bar{\mu}\frac{\partial u}{\partial r} \tag{1}$$

$$\bar{\rho}\frac{\partial v}{\partial t}+\bar{\rho}u\frac{\partial v}{\partial x}+\bar{\rho}v\frac{\partial v}{\partial r}=-\frac{\partial p}{\partial r}+\frac{\partial}{\partial x}\bar{\mu}\frac{\partial v}{\partial x}+\frac{1}{r}\frac{\partial}{\partial r}r\bar{\mu}\frac{\partial v}{\partial r}-\bar{\mu}\frac{v}{r^2} \tag{2}$$

$$\frac{\partial\bar{\rho}}{\partial t}+\frac{\partial\left(\bar{\rho}u\right)}{\partial x}+\frac{1}{r}\frac{\partial\left(r\bar{\rho}v\right)}{\partial r}=0 \tag{3}$$

$$\bar{\rho}\bar{c}\frac{\partial T}{\partial t}+\bar{\rho}\bar{c}u\frac{\partial\left(\bar{\rho}u\right)}{\partial x}+\bar{\rho}\bar{c}v\frac{\partial T}{\partial r}=\frac{\partial}{\partial x}\bar{\lambda}\frac{\partial T}{\partial x}+\frac{1}{r}\frac{\partial}{\partial r}r\bar{\lambda}\frac{\partial T}{\partial r}-\dot{m}Q \tag{4}$$

$$\bar{\rho}\frac{\partial Y}{\partial t}+\bar{\rho}u\frac{\partial Y}{\partial x}+\bar{\rho}v\frac{\partial Y}{\partial r}=\dot{m}\,. \tag{5}$$

The specific mass rate of the vapor formation is found from the heat balance equation: $\dot{m}=\left(\bar{\rho}\bar{c}\Delta T^{*}\right)\Big/Q$, where the reduced heat flow is defined according to the following equation: $\Delta T^{*}=\begin{cases}0, \text{ if } \; T\left(t+\Delta t\right)<T_S\\ \left[T\left(t+\Delta t\right)-T\left(t\right)\right]\Big/\Delta t, \text{ if } \; T\left(t+\Delta t\right)>T_S\end{cases}$

$T\left(t\right)=\max\left(T\left(t\right);\; T_s\right)$, Δt - time step, T_s - saturation temperature. The energy equation for the metal cylinder $0<r<r_m$ has the following form:

$$\rho_m c_m\frac{\partial T_m}{\partial t}=\frac{\partial}{\partial x}\lambda_m\frac{\partial T_m}{\partial x}+\frac{1}{r}\frac{\partial}{\partial r}r\lambda_m\frac{\partial T_m}{\partial r} \tag{6}$$

The boundary conditions are as follows: at $x=0$ and $r_m<r<r_l$; $T=T_{0l}$, $u=u_0$, and $v=0$.

$r=r_m$: $-\lambda_m\frac{\partial T_m}{\partial r}=-\bar{\lambda}\frac{\partial T}{\partial r}$, $T_m=T$, $u=0$, $v=0$. For the outer boundaries: $\frac{\partial\Gamma}{\partial y}=0$, $\Gamma=\left\{T,u,v\right\}$, $y=\left\{x,r\right\}$.

3. Calculation results

Let us compare the results obtained with the use of the offered mathematical model allowing solving the conjugate problem of convective heat exchange taking into account the vapor formation with the results calculated by the mathematical model using criterial equations for determining the boundary conditions on the cylinder surface at the contact with the water flow. Let us consider cooling a solid metal cylinder borrowing the initial data from [11]: $r_m = 0.01$ m, $r_l = 0.013$ m, $L = 0.2$ m, $T_{0l} = 20$ °C. Let us take $r_a = 0{,}1$ m, the air initial temperature $T_{0a} = T_{0l}$, the initial temperature of the cylinder $T_m = 950$ °C, the saturation temperature $T_s = 100$ °C, and the water flow rate u0 = 12 m/s. The calculation time is 10 s. The thermophysical parameters of the media are taken according to [22,23].

It can be seen (Fig. 3) that the value of the temperature at the point 1 (Fig. 2) calculated with the help of the mathematical model offered in the present paper and the temperature value at the point 1' received for the same point using the mathematical model, where the determination of the boundary conditions on the cylinder surface is based on the criterial equations, differ only within the initial time interval equal to 3 s. This cannot be said about the points 2 and 2'; there is an obvious difference in the temperatures of the cooled cylinder surface. The temperature value variation at the point 2 after 0.8 s is due to the vapor formation process taking place on the high-temperature cylinder surface. Thus, the criterial equations used for determining the boundary conditions sometimes incorrectly determine the temperature values in a work piece, especially when the temperature variations along the cooled surface and the presence of vapor are taken into consideration.

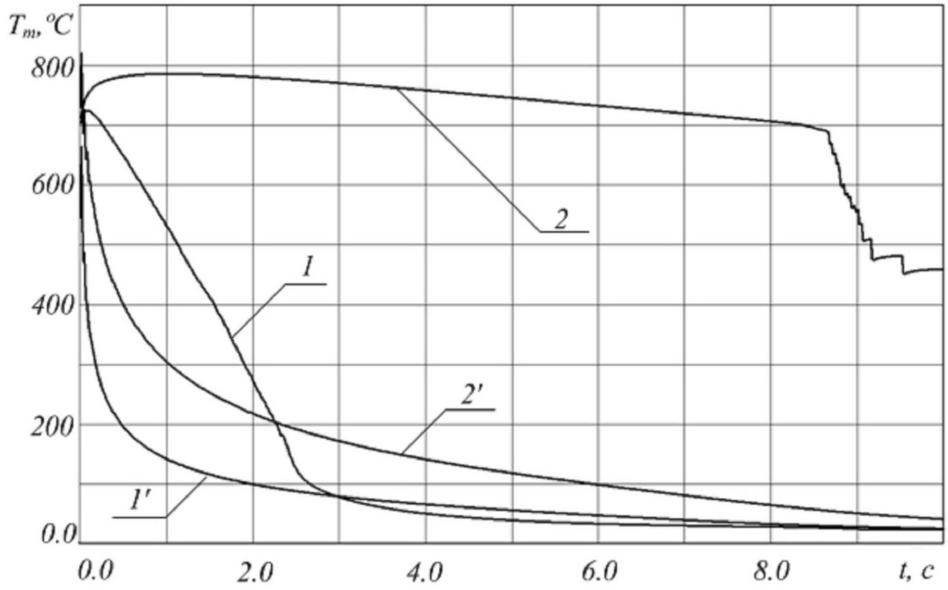

Fig. 3. The temperature of the cylinder surface at the calculation points:1, 2 – the temperatures calculated with the use of the offered model; 1', 2' – the temperatures calculated using the model described in [11].

Figure 4 shows the temperature in the middle of the cylinder surface. The initial data are the same as those taken previously. The water flow rate is 1 m/s. The calculation time is 30 s. The calculation is performed for both cases when the presence of vapor on the cylinder surface $Y > 0$ is taken into account and when it is not taken into account, $Y = 0$.

From the calculation results it follows that at high temperatures the presence of vapor slows down the heat removal from the cylinder surface (in the given case it is 600 °C), and at lower temperatures, the intensity of cooling increases. Thus, when the vapor presence in the liquid flow is neglected like in [9-11, 24], the value of the calculated temperatures can differ by 50% and more.

In Fig. 5, the temperatures in the middle of the cylinder surface are given at the initial cylinder temperature Tm = 350 °C and at cooling by the water flow at the rates 1m/s, 5 m/s, and 10 m/s.

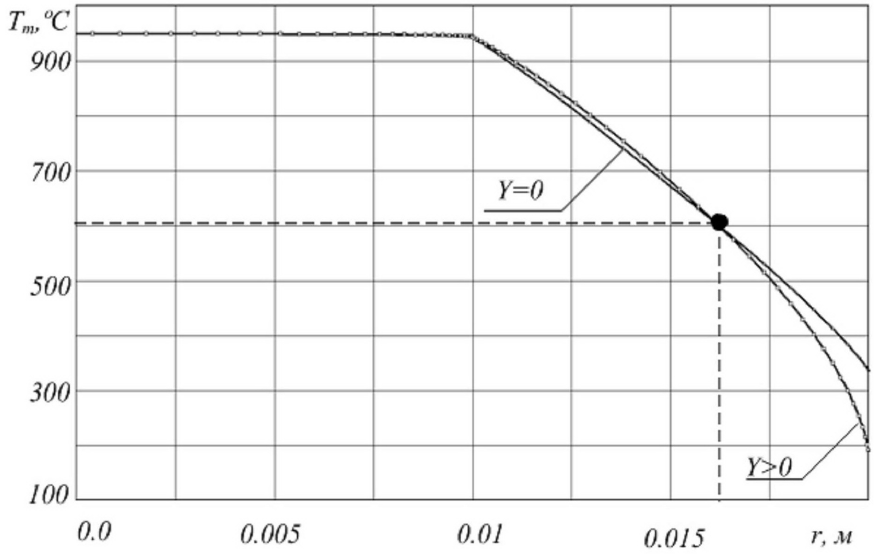

Fig. 4. The temperature in the middle of the cylinder surface when the presence of vapor $Y > 0$ is taken into account, and when the presence of vapor $Y = 0$ is not taken into account.

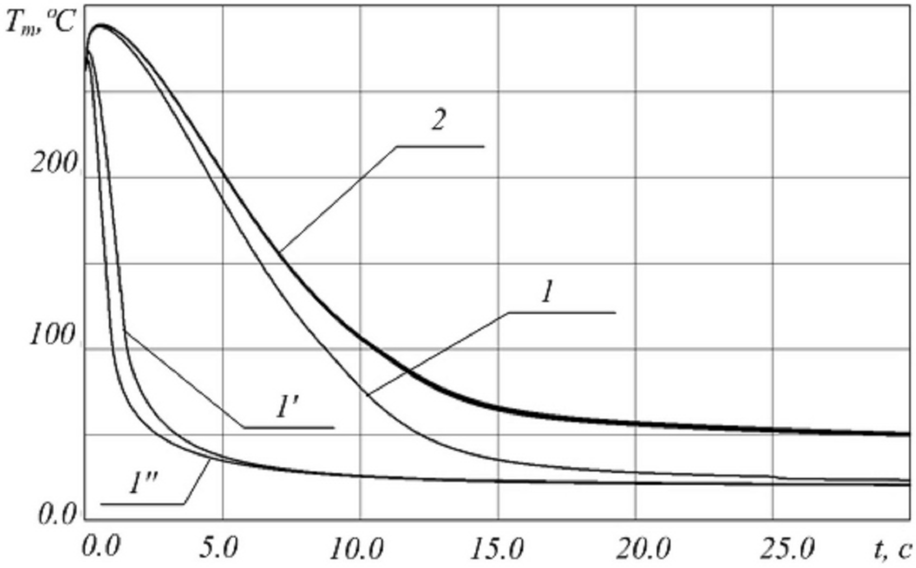

Fig. 5. The temperature of the cylinder surface at the calculation points at the water flow rates: 1 – 1 m/s, 1' – 5 m/s, and 1'' – 10 m/s; 2 – 1 m/s, 5 m/s, 10 m/s.

When all the other conditions are equal, the higher the water flow rate is, the lower the received values of the temperature at the calculation points are. This regularity is more obvious in the initial region of the cooled surface. At the calculation point 1 within the time 5 s, the difference in the temperatures makes up 45% at the rates 1 m/s and 10 m/s. At the calculation point 2, when the rate of the flow decreases from 10 m/s to 1 m/s, the temperature increases by 4%, i.e. it remains practically the same for all the considered values of the water flow rate.

4. Conclusion

The offered mathematical model of the process of cooling high temperature cylinder work pieces and the results of the mathematical modeling can be used for solving mathematical problems of finding initial heat and hydrodynamic conditions for the calculation of heat-stressed processes in metallurgy and mechanical engineering, for example, for the calculation of the parameters of cooling high-temperature cylindrical metal work pieces depending on geometry and thermophysical properties of cooled material and cooling media, and the time of the process.

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