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Mathematical Modeling of Cooling High-Temperature Cylindrical Workpieces

S.S. Makarov[a,*], V.B. Dement'yev[a], E.V. Makarova[b]

[a] *Institute of Mechanics of Ural Branch of the Russian Academy of Sciences, 34, T. Baramzinoy St., Izhevsk, 426067, Russia*
[b] *Kalashikov Izhevsk State Technical University, 7, Studencheskaya St, Izhevsk,426069, Russia*

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;

* Corresponding author. Tel.: +7(3412) 508 200; fax: +7(3412) 507 959.
E-mail address: ssmak15@mail.ru

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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
$\left\{\overline{\rho},\overline{c},\overline{\lambda},\overline{\mu}\right\} = f\left(Y\right)$

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