Heat exchange numerical modelling while cooling a high-temperature metallic cylinder by water and air medium flow

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Abstract. The results of numerical modeling of heat transfer during the cooling of a metal cylinder by a stream of water-air medium in a vertical annular channel are presented. The results are obtained on the basis of the mathematical model of the conjugate heat transfer of the water-air medium flow and a metal cylinder in a two-dimensional nonstationary formulation, taking into account the axisymmetry of the cooling medium flow with respect to the longitudinal axis of the cylinder. To solve the system of differential equations, the control volume method is used. The flow field parameters are calculated by the SIMPLE algorithm. For the iterative solution of linear algebraic equation systems, the Gauss-Seidel method with lower relaxation was used. The results of calculating the heat transfer parameters for cooling high-temperature metal cylinder by a stream of a water-air medium stream are obtained taking into account the evaporation. The values of a metal cylinder temperature are determined when cooled by a laminar flow medium. The intensity of the change in the cooling rate of the cylinder is analyzed depending on the proportion of air in the liquid and the time of the cooling process.

1. Introduction
In [1], a mathematical model of conjugate heat transfer in a heterogeneous solid-gas-liquid medium system is proposed. The two-dimensional temperature field in liquid and solid bodies is determined when the conjugation condition is fulfilled at the interface of the media. Additionally, the vaporization was counted at the surface of a high-temperature metallic body of a cylindrical shape, cooled by a longitudinal flow of water. The numerical algorithm is applied to the study of heat transfer during cooling of a high-temperature cylindrical metal billet of structural steel with a stream of gas-liquid medium [2, 3].

The purpose of this work is to simulate heat transfer during cooling of a high-temperature metal cylinder with a stream of water containing air in a vertical annular channel to find out how heat transfer parameters influence on the cooling rate of the cylinder. Figure 1 shows the scheme of the model under consideration.
A metal cylinder of radius $r_m$ and length $L$ is cooled by a fluid flow moving in the direction of the vertical axis $x$ in the annular gap $r_1 - r_m$ with the initial velocity $u_0$. The outer radius of the metal wall $r_m$.

In this paper, we consider a mathematical model of the coupled heat exchange of a gas-liquid medium flow and a metal cylinder in a two-dimensional axisymmetric nonstationary formulation. The system of equations describing the flow of the water-air medium, taking into account the formation of steam in the fluid flow, has the form:

$$\rho \frac{\partial u}{\partial t} + \rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial r} = -\rho g - \frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left( \mu \frac{\partial u}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( \mu \frac{\partial u}{\partial r} \right) \quad (1)$$

$$\rho \frac{\partial v}{\partial t} + \rho u \frac{\partial v}{\partial x} + \rho v \frac{\partial v}{\partial r} = -\frac{\partial p}{\partial r} + \frac{\partial}{\partial x} \left( \mu \frac{\partial v}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( \mu \frac{\partial v}{\partial r} \right) - \frac{\rho v}{r^2} \quad (2)$$

$$\frac{\partial p}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{1}{r} \frac{\partial (r \rho v)}{\partial r} = 0 \quad (3)$$

$$\rho c \frac{\partial T}{\partial t} + \rho c u \frac{\partial T}{\partial x} + \rho c v \frac{\partial T}{\partial r} = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( \lambda \frac{\partial T}{\partial r} \right) - \dot{m}_v Q_v - \rho g u \quad (4)$$

$$\rho \frac{\partial Y_u}{\partial t} + \rho u \frac{\partial Y_u}{\partial x} + \rho v \frac{\partial Y_u}{\partial r} = 0 \quad (5)$$

$$\rho \frac{\partial Y_v}{\partial t} + \rho u \frac{\partial Y_v}{\partial x} + \rho v \frac{\partial Y_v}{\partial r} = \dot{m}_v \quad (6)$$

Specific mass vaporization rate is: $\dot{m}_v = (\rho c \Delta T)/(Q_v \Delta t)$,

where $\Delta T = \begin{cases} 0, \text{ если } T(t + \Delta t) < T_s \\ \left[ T(t + \Delta t) - T_s(t) \right], \text{ если } T(t + \Delta t) > T_s \end{cases}$ = liquid overheating;

$T_s(t) = \max[T(t); T_v]$. 

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1 - metal cylinder; 2 - outer wall; 3 - fluid flow; 4 - camera; 5 - fitting, [4]

1 - metal cylinder; 2 - cylinder axis; 3 - fluid flow; 4 - outer wall

**Figure 1.** Physical and computational schemes of the model.
The value $\Delta T$ can take both positive and negative values. In the first case, the cost of thermal energy for the phase transition of the liquid into steam is taken into account. In the second case, the thermal effect of vapor condensation into a liquid is taken into account, provided that there is vapor in the medium, i.e. $Y_v > 0$.

Thus, the energy heat and mass transfer balance of the system is regulated.

The energy equation for a metal cylinder and an outer metal wall can be presented as follows:

$$\rho_m c_m \frac{\partial T_m}{\partial t} = \frac{\partial}{\partial x} \lambda_m \frac{\partial T_m}{\partial x} + \frac{1}{r} \frac{\partial}{\partial r} r \lambda_m \frac{\partial T_m}{\partial r}.$$  \hspace{1cm} (7)

The effective thermophysical parameters of the gas-liquid medium are determined as follows [5]:

$$\rho = \sum_3 \rho_i, \ c = \sum_3 c_i \rho_i / \rho, \ \lambda = \frac{1}{2} \left[ \sum_3 Y_i \lambda_i + \left( \frac{\sum Y_i}{\lambda_i} \right)^{-1} \right], \ \mu = \frac{1}{2} \left[ \sum_3 Y_i \mu_i + \left( \frac{\sum Y_i}{\mu_i} \right)^{-1} \right],$$

$$\sum_3 Y_i = 1.$$ 

Initial conditions: $u = u_0, \ v = 0, \ T_l = T_{l0}, \ T_m = T_{m0}, \ T_{ml} = T_{l0}, \ Y_a = Y_{a0}$.

Border conditions:

$$x = 0: 0 < r < r_m, \quad \frac{\partial T}{\partial x} = 0$$

$$r_m < r < r_i, \quad T = T_{l0}, \ u = u_0, \ v = 0, \ Y_v = 0, \ Y_a = Y_{a0}, \ \frac{\partial p}{\partial x} = 0$$

$$r_i < r < r_{ml}, \quad \frac{\partial T}{\partial x} = 0$$

$$x = L: 0 < r < r_m \quad \frac{\partial T}{\partial x} = 0$$

$$r_m < r < r_i \quad \frac{\partial T}{\partial x} = 0, \ \frac{\partial u}{\partial x} = 0, \ \frac{\partial v}{\partial x} = 0, \ \frac{\partial Y_v}{\partial x} = 0, \ \frac{\partial Y_a}{\partial x} = 0, \ p = 0$$

$$r_m < r < r_{ml} \quad \frac{\partial T}{\partial x} = 0,$$

$$0 < x < L: r = 0 \quad \frac{\partial T}{\partial r} = 0$$

$$r = r_m, \quad -\lambda_m \frac{\partial T_m}{\partial r} = -\lambda_i \frac{\partial T_i}{\partial r} \quad T_m = T_i, \ u = 0, \ v = 0, \ \frac{\partial Y_v}{\partial r} = 0, \ \frac{\partial Y_a}{\partial r} = 0$$

$$r = r_i \quad -\lambda_{ml} \frac{\partial T_{ml}}{\partial r} = -\lambda_i \frac{\partial T_i}{\partial r} \quad T_{ml} = T_i, \ u = 0, \ v = 0, \ \frac{\partial Y_v}{\partial r} = 0, \ \frac{\partial Y_a}{\partial r} = 0$$

$$r = r_{ml} \quad \frac{\partial T}{\partial r} = 0.$$ 

The local cooling rate in the volume of the metal cylinder will be determined as follows:
The system of differential equations (1) - (7) is solved by the method of control volume. The parameters of the flow field (1) - (3) are calculated, by means of the SIMPLE algorithm used in modeling fluid flow with heat and mass transfer [6]. Differential equations are reduced to a system of linear algebraic equations and are solved iteratively by Gauss-Seidel method using the lower relaxation coefficient. For the calculations, a grid with a condensing profile at the boundaries of the metal cylinder-liquid and liquid-external metal wall from the liquid and metal sides is used. The calculation step in the longitudinal coordinate is constant.

2. Research results
As it is known, there are various kinds of inclusions in water, including air and other gases, which are either dissolved in a liquid or present in the form of tiny bubbles in the volume of a liquid. In [1-3], the numerical results of coupled heat transfer during cooling of a high-temperature metal cylinder with a water flow were obtained without taking into account the presence of air.

Let us consider the case when water initially contains a constant amount of air, given as a volume fraction. Of course, the natural content of air in water is insignificant, and under normal conditions it ranges from 1% to 2.5% [7]. However, in real technological cooling processes, it is possible to obtain water-air mixtures with an arbitrary fraction of air while maintaining the continuity of the main fluid flow [8].

As it was shown by previous studies, a boundary liquid layer of 1 mm is involved in the heat exchange between the fluid flow and the metal body heated to a high temperature. In this regard, the influence of thermophysical properties and composition of the cooling medium on the conditions of heat removal from a heated body, at high heat flux, has one of the decisive values.

For the study, we assume that the cylinder material is 12H18N9T steel, the geometrical dimensions are: \( r_m = 0.015 \) m, \( r_l = 0.025 \) m, \( r_{m1} = 0.03 \) m, \( L = 0.1 \) m. Initial temperature is \( T_{m0} = 840 \) °C. Calculation time 1 s.

Figure 2 shows the results of numerical calculations of the surface temperature of a metal cylinder at the initial flow rate of water \( u_0 = 0.1 \) m/s and the values of the volume fraction of air: 1 - \( Y_a = 0 \); 2 - \( Y_a = 0.025 \).

![Figure 2. Surface temperature of a metal cylinder.](image)

The results show that the presence of air in a stream of water, ceteris paribus, leads to an increase in the surface temperature of the cooled metal cylinder. So, for the settlement period, the difference is 22 °C, which is 4% of the temperature increase for the case when air is taken into account.

Figure 3 shows the values of the cooling rate on the surface in the middle of the cylinder, depending on the volume fraction of air in the water flow.
Figure 3. Cooling rate on the surface in the middle of the cylinder.

It is seen that taking into account the presence of air in the flow of water leads to a decrease in the cooling rate of the metal cylinder. In the initial time interval, the difference in the cooling rate reaches 161 °C/s, which is 32% lower than the calculated case without taking into account the presence of air.

Figure 4 shows the cooling rate in the middle of the cylinder along the radius, depending on the volume fraction of air \( Y_a \) in the water flow.

Figure 4. Cooling rate along the radius in the middle of the cylinder.

It can be seen that the cooling rate in the radial direction tends to decrease similarly to the cooling rate of the surface of a metal cylinder. So for the calculating period, air accounting in the water flow led to a decrease in the cooling rate by 10 °C/s, which is 12% lower compared to the design case without taking into account the presence of air.

3. Conclusion

Based on the model of coupled heat exchange, the results of the cooling parametric study of a high-temperature metal cylinder by a longitudinal flow of an air-water medium were obtained. A qualitative and quantitative assessment of the effect of the proportion of air in the water flow on the cooling rate of a metal cylinder is given. The developed model can be applied in a variety of technical applications related to the process of cooling high-temperature metallic bodies.

References

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