CAPACITY OF THE INTERSTAND COOLING UNIT IN HOT ROLLING PROCESS

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Abstract

The aim of the paper was to improve the economy of rolling mill production and to extend the control range of cooling capacity of the accelerated cooling unit by choosing the optimal dimensions of the cooling chamber. The object of research was the interstand cooling unite for accelerated cooling of the hot-rolled products of round section in the line of continuous rolling mill in order to reduce the machine time rolling or even eliminate completely the requirement for heat treatment of the hot-rolled products in heat-treatment furnaces. The influence of the design parameters of the cooling chamber on the expanding the control range, retaining a high cooling capacity of the chamber, was investigated by the numerical model based on the finite difference method. The diagrams presented in the paper allow determining the diameters of the cooling chamber, which provide a wide control range of the chamber cooling capacity and minimization of energy consumption of the electric water pump.

Keywords: hot rolling, accelerated cooling, finite difference modelling

1 Introduction

In practice, during hot rolling process, the evolution of the microstructure is connected with physical processes taking place in the deformed steels, such as recrystallization, precipitation and phase transformation, depending on the chemical composition and particular parameters of the metal forming process, i.e. the strain, strain rate and temperature. Thermomechanical Controlled Processing (TMCP) including accelerated cooling is a well-established technology, widely applied in steel rolling production in order to produce a material with the desired microstructures and mechanical properties as well as to reduce the machine time rolling or even eliminate completely the requirement for heat treatment of the hot-rolled products in heat-treatment furnaces [1-5].

In order to reduce the production cost and to improve the quality of hot-rolled steel round products of small-section in the line of continuous mills, the technology of accelerated interstand cooling is used. By using this technology, the hot-rolled products with the desired microstructures and mechanical properties have been produced and the cost of energy to heat the metal in special heat-treatment furnaces is decreased [6-8].

The object of research in this paper was the interstand cooling unit for accelerated cooling of the hot-rolled products of round section in the line of continuous mill. The characteristics of the

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cooling unit operation is determined by its dimensions (length and diameter of the cooling chamber), and the mutual movement of rolled steel and water (co-current or counter-current). The presence of the upper and lower limits of the cooling capacity appears particularly in the co-current cooling chambers due to the limitations relating to the temperature of the waste water. In the design of a new cooling unit the main task is to determine the dimensions of the cooling chamber and their impact on the technological parameters of the cooling process [9-13].

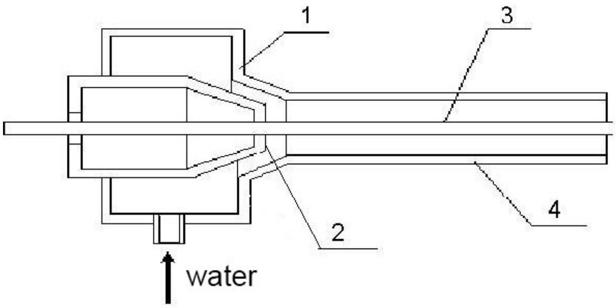
To solve these problems, the mathematical model of the cooling process of the hot-rolled products of round section was formulated. In this paper the influence of the design parameters of the cooling chamber on the expanding the control range, retaining a high cooling capacity of the chamber, was investigated by this numerical model based on the finite difference method and the solution of the differential equation of heat conduction in cylindrical coordinates under the boundary conditions of the third kind. The model allows investigating the influence of the design parameters of the cooling chamber on the technological regimes, the cooling performance and energy efficiency of the cooling unit.

As a result of the conducted numerical experiment was established that the main bottleneck in choosing the diameter of the cooling chamber is the water pressure provided by the pump, and the water temperature at the outlet of the cooling chamber. These parameters define the upper and lower limiting values of the chamber cooling capacity.

The diagrams presented in the paper allow determining the diameters of the cooling chamber, which provide a wide control range of the chamber cooling capacity and the minimization of energy consumption of the electric water pump.

2 Unit for accelerated cooling

Lately, the rolled products are mainly processed in the chamber type unites for accelerated cooling. **Fig. 1** shows a schematic diagram of the unit for accelerated cooling and thermal processing of hot-rolled metal. The accelerated cooling unit consists of the chamber of cylindrical type in which the cooling water under pressure is supplied, and flows along the chamber axis. Depending on the direction of motion of rolled steel and cooling water, the different modes of flows are established: co-current, counter-current and co-counter-current.



1 – case of injector, 2 - annular nozzle, 3 - cooled steel, 4 - cooling chamber

Fig. 1 Schematic diagram of the accelerated cooling unit

The counter-current flow mode is more efficient in terms of heat transfer. The advantage of co-current cooling mode, especially at the smaller cross-section of rolled steel in front of the chamber, is possible appearance of the effect of hydrotransportation of the rolled steel, but the cooling rate at such a mode is 4÷5 times less than in counter-current mode at the same water flow rate [14].

Unites for accelerated cooling may be made up of one long section, which provides a rapid cooling over the metal cross-section, or may consist of a few short sections that provide a more gradually cooling on a longer chamber length [15].

3 Numerical model

In the course of cooling the rolled steel into chambers, under production conditions, is practically impossible to measure the temperature of steel during the cooling process. However, this temperature can be calculated by the mathematical model, which is based on the equations of heat transfer.

The steel during the rolling process has the cross sectional shape, which is close to a circle. The basis of the mathematical model of cooling of round cross-section rolled steel is the differential equation of heat conduction in cylindrical coordinates [16]:

$$c \cdot \rho \cdot \frac{\partial T}{\partial t} = \frac{\partial}{\partial r}\left(\lambda \cdot \frac{\partial T}{\partial r} \right) + \frac{\lambda}{r} \cdot \frac{\partial T}{\partial r}, \qquad (1.)$$

where c is the specific heat capacity, J/(kg·K), ρ is the density, kg/m^3, and λ is the thermal conductivity of the steel, W/(m·K), t is the time, s, r is the coordinate along the radius, m, T is the temperature of the steel, K.

During the process of steel cooling its surface temperature can vary over a considerable range from an initial steel temperature to a temperature of cooling water. Therefore, the model uses the boundary conditions of the third kind:

- within the cooling chamber the convective heat transfer between the steel surface and the water is described by the equation

$$-\lambda \cdot \frac{\partial T}{\partial r} = \alpha \cdot \left(T_{\mathrm{w}} - T \right) \quad \text{at} \quad r = R, \qquad (2.)$$

  where α is the coefficient of heat transfer from the steel to the water, W/(m^2·K), T is temperature of the steel surface, K, T_{w} is the water temperature, K, R is the radius of the profiled steel, m;

- the radiant and convective heat transfer in the direction of environmental air (outside of the cooling chamber) is described by the equation

$$-\lambda \cdot \frac{\partial T}{\partial r} = \alpha_{\mathrm{air}} \cdot \left(T_{\mathrm{air}} - T \right) + \sigma \cdot \left(T_{\mathrm{air}}^4 - T^4 \right) \quad \text{at} \quad r = R, \qquad (3.)$$

  where α_{air} is the coefficient of convective heat transfer from the steel to the air, W/ (m^2·K), T_{air} is the ambient temperature, K, σ is the radiation coefficient of the steel, W/(m^2·K^4).

Before entering the cooling chamber the temperature over the steel cross-section is uniform, i.e.

$$T(r) = T_0 \quad \text{at} \quad t = 0 \qquad (4.)$$

where T_0 is the temperature of the steel before entering the cooling chamber, K.

The average value of heat transfer coefficient along the chamber is determined according to the criterion function proposed in Ref. [12]. The pressure and temperature of the water, in the formula for determining the water properties, are defined as the arithmetic mean values along the chamber length. The useful pump power is calculated as the product of the water pressure (p, Pa) generated by the pump, and the water flow rate in the chamber (q_V, m^3/s). To solve the heat equation with the boundary conditions, the finite difference method was used [17].

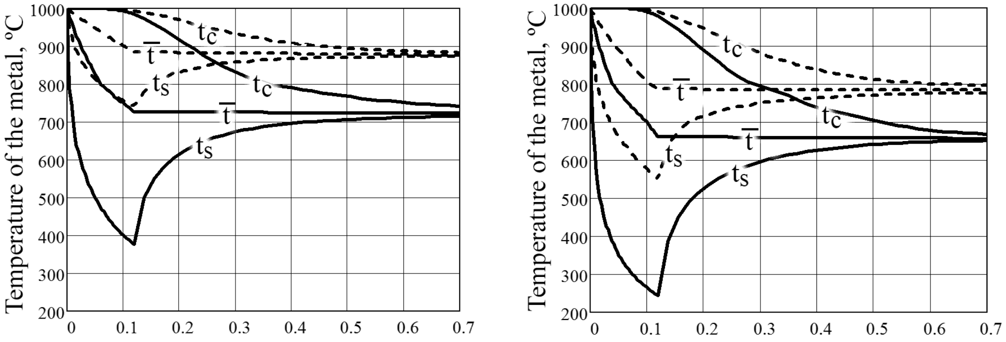
4 Discussion of results

The initial data for the numerical experiment were as follows:

- The length of the cooling chamber is 3 m;
- The diameter of the rolled steel is 6.5 mm;
- The initial temperature of the water is 20°C;
- The rate of the rolled steel is 25 m/s;
- The initial temperature of the rolled steel is 1000°C;
- The water-cooled material is mild steel;
- The steel emissivity is 0.8.

The calculations are performed at the variable thermal properties of the steel [18] and the variable physical parameters of the water at the saturation line [12]. The water temperature at the outlet of the cooling chamber ranges from 40°C [12] to 80°C [19]. The higher water temperature, over a period, can put out of service the cooling device because of the possibility of salt deposits in its drainage channels [20]. Also, at a high temperature of the water increases the probability of non-uniform cooling along the length of rolled steel because of the danger appearance of a vapour lock in the chamber sections. The water pressure generated by the pump, it was limited to 50 bar, which corresponds to the operation of accelerated cooling unites in practice.

The research results of the cooling capacity obtained for the co-current and counter-current cooling modes are presented in **Fig. 2**. In this paper the chamber cooling capacity means the difference of average temperatures over the cross-sections of rolled steel before and after the cooling chamber.



a) co-current mode (D=21 mm);
—— water consumption 40 m^3/h;
- - - - water consumption 7 m^3/h

b) counter-current mode (D=30 mm);
—— water consumption 40 m^3/h
- - - - water consumption 14 m^3/h

Fig. 2 Temperature change of the rolled steel in the course of cooling in the co-current and counter-current mode (t_s – surface temperature; t_c – core temperature; $\bar{t}$ – bulk temperature)

The diameter of cooling chamber was defined under the condition of providing the maximum control range of the chamber cooling capacity at the given constraint on the water flow rate of 40 m^3/h, which value allows comparison between the pump energy consumptions. The control range of the chamber cooling capacity means the difference between maximum and minimum cooling capacity of the chamber. Thus, it is possible to compare the chamber efficiency for different cooling modes.

The lower limit of the chamber cooling capacity is determined by the water temperature at the outlet of the chamber of 80°C. **Fig. 2** shows that the residence time of rolled steel in the cooling chamber, at the given chamber length and the rate of rolled steel, is only 0.12 seconds. Therefore, after the rolled product left the chamber by going into the air, the temperature equalization over the cross-section occurs.

In the co-current cooling chamber (**Fig. 2a**), the water temperature at the outlet of the chamber is in the range of 80÷55°C, for the lower and upper limits of water consumption, respectively. By reducing the water consumption below 7 m^3/h, the water temperature at the outlet of the cooling chamber exceeds 80°C, which can affect the quality of cooling. The cooling capacity of the chamber is in the range 110÷260°C. Consequently, the control range of chamber cooling capacity is 150°C.

Similarly, in the counter-current chamber (**Fig. 2b**), the water temperature at the outlet of the chamber is in the range of 80÷60°C, and the chamber cooling capacity is in the range 210÷340°C. Consequently, the control range of chamber cooling capacity is 130°C.

The necessary pump power to ensure the water flow rate of 40 m^3/h (the upper limit of the cooling capacity) for the co-current cooling chamber is 50 kW and 27 kW for the counter-current chamber. Accordingly, the necessary pump power for the lower cooling capacity of the co-current cooling chamber is in excess of 46%. To provide a dipper cooling of the steel, it is rational to use the counter-current cooling mode, as the less pump power is required.

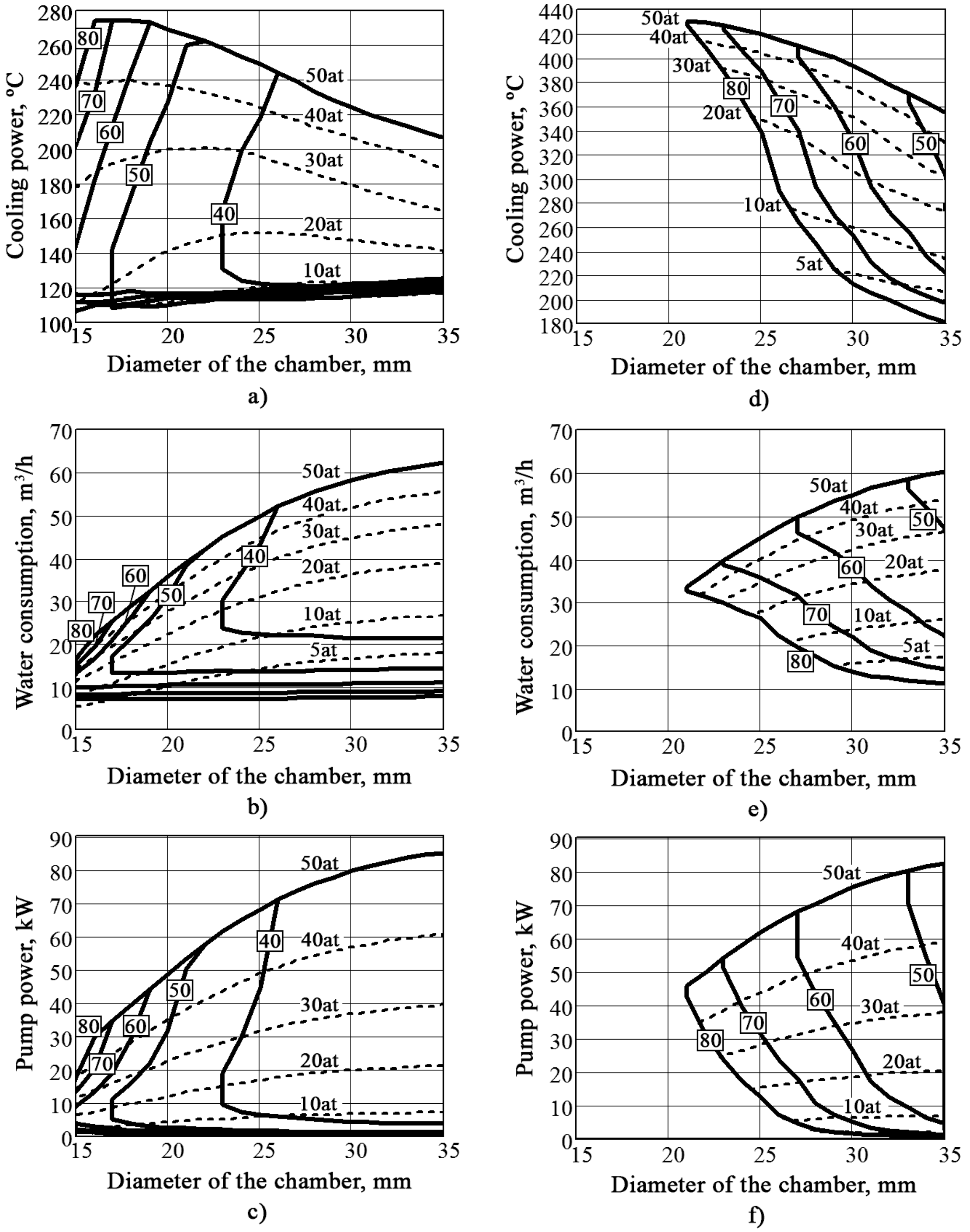
In **Fig. 3** the chamber cooling capacity, water consumption and pump power are shown as the function of the chamber diameter, the water temperature at the outlet of the chamber and the water pressure generated by the pump, for the co-current and counter-current chambers at the same chamber length of 3 m.

By means of these diagrams, the optimum dimensions of the accelerated cooling chamber can be determined. For example, at the outlet water temperature of 60°C and the pressure of 50 bar, the optimal diameter for the co-current chamber is in interval of 18÷20 mm, and for the counter-current chamber is in excess of 27 mm.

It was noted earlier that the use of co-current cooling mode in comparison with counter-current has a under capacity, which does not allow a deeper metal cooling. The advantage of co-current mode is in the enhanced control range.

The maximum cooling capacity of the co-current chamber, with the optimal chamber diameter, corresponds to the widest range of cooling capacity. With a decrease in the diameter of co-current chamber it is possible that the caused reduction in cooling capacity is accompanied by a reduction of energy costs.

In counter-current chambers the maximum cooling capacity corresponds to the range of cooling capacity which is equal to zero. At counter-current cooling mode the reduction in cooling capacity (relative to the maximum), by changing the chamber diameter, is possible only with increased diameter, which is always accompanied by an increase in energy costs. It should be noted that a decrease in cooling capacity of the co-current chamber (relative to the maximum) causes the decreased range of the cooling capacity.



a, b, c) co-current chamber d, e, f) counter-current chamber

Fig. 3 Efficiency of the co-current and counter-current cooling chambers

5 Conclusion

1. Extension of the control range of the chamber cooling capacity in hot rolling mill production depends mainly on the design parameters of the chamber (length and diameter) and the cooling mode (co-current and counter-current).

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2. The upper and lower limits of the cooling capacity of the chambers are determined. The upper limit corresponds to the value of water flow rate, above which the water temperature at the outlet of the chamber exceeds the acceptable value, due to the increase of heat transfer coefficient or because of restrictions on the water pressure, i.e. on the water pump. The lower limit corresponds to the water flow rate, under which the water temperature at the outlet of the chamber exceeds the acceptable value, due to the lack of water flow.
3. Presented diagrams allow determining the optimal values of diameters for the co-current and counter-current cooling chambers under given constraints on the temperature of the outlet water and the pump pressure.

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