International Journal of Heat and Mass Transfer 128 (2019) 526–535

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Optimization of influence factors for water cooling of high temperature plate by accelerated control cooling process

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ARTICLE INFO

Article history:
Received 4 July 2018
Received in revised form 28 August 2018
Accepted 6 September 2018

Keywords:
Accelerated control cooling
Heat transfer coefficient
Plate water cooling optimization
Precise plate cooling
Water temperature effect

ABSTRACT

The accelerated control cooling is considered to be one of the most practical technologies in the high tensile strength steel manufacturing industry. In order to achieve a high precision required for the cooling process, the system modeling should be done and optimized by considering the heat transfer mechanism as much as possible. For the system optimization, the parametric analysis for the influence factors such as feed water temperature, plate speed, plate width and specific heat should be carried out. In this study, we focus on optimizing the influence factors during water cooling of high temeperature plate by the accelerated control cooling process. The scale analysis with Reynolds and Prandtl numbers is made to optimize the effect of feed water temperature, and then the water flow density is determined during the water cooling process. The cooling efficiency is calculated in order to optimize the plate speed and plate width. Finally, start cooling temperature(SCT) and finish cooling temperature(FCT) are optimized by comparing the specific heat of standard references about low carbon steel such as NIST-JANAF, Eurocode, ISIJ. It is concluded that the accuracy of the predicted finish cooling temperature and the stability of the cooling process are significantly improved after the optimization of influence factors.

1. Introduction

The representative method to improve the mechanical properties of steel with the same chemical composition is to control start cooling temperature (SCT) and finish cooling temperature (FCT) and cooling rate. The thermal mechanical properties with the same chemical composition can be improved by the method, called “accelerated control cooling process”. The cooling process by precise water cooling makes many things possible such as getting more fine grain size, controlling microstructures and strength and yield ratio, improving the toughness of plate [1–5]. It allows designing ships or buildings to be lighter, loading more luggage with efficient use of space. And it is possible to delay the collapse of buildings during the earthquakes, and to prevent low temperature brittleness even in low temperature environment, so that it is possible to secure stability against buildings and ships even in polar regions.

The precise water cooling means that the cooling model predicts the FCT after cooling process from measured SCT with a given cooling rate. Basically, the finite volume method (FVM) is applied for precise cooling to analyze temperature distribution and heat transfer process in the plate. With the FVM application, the heat transfer coefficient with standard conditions is used as a reference value. It could be optimized by correcting the deviation between predicted and measured values. And the adapted efficiency by the deviation could be expressed as the cooling efficiency. Despite of a high adapting efficiency of water cooling, there is deviation between the predicted and measured values. The main causes are the effects of influence factors such as deviation of heat transfer coefficient according to water temperature, change of plate speed and dimension, deviation of specific heat according to temperature and components of chemistry. To reduce the deviation of predicted temperature, the influence factors should be optimized.

First of all, the feed water temperature may be considered as the influence factor in the supply system. The cooling water temperature changes several times a day in closed loop system because the cooling tower is usually designed to be used in the range of 278–328 K in industry equipment. This phenomenon has a great influence on the heat transfer coefficient of water cooling and on the calculation of required water flow density. Sasaki et al. [6] studied the effect of water flow rate and surface temperature and water temperature on the cooling performance. They concluded that the effects of water flow rate and surface temperature were remarkable while the effect of water temperature could be neglected in water spray cooling. However, Raudensky et al. [7]

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.09.024
0017-9310/© 2018 Published by Elsevier Ltd.

Nomenclature

C_p	specific heat, J/kg K
g	gravitational acceleration, m/s^2
Gr	Grashof number
h_C	convective heat transfer coefficient of air, W/m^2 K
h_R	radiative heat transfer coefficient of air, W/m^2 K
h_{Air}	total heat transfer coefficient of air, W/m^2 K
L	characteristic length, m
Nu	Nusselt number
Pr	Prandtl number
Ra	Rayleigh number
t	time, s
T	temperature, K
T_{th}	thickness, mm
X	measurement value
$\overline{X}$	measurement mean value

Greek symbol

β	Stephan Boltzmann constant, W/m^2 K^4
λ	thermal conductivity, W/m K
ε	emissivity
ζ	cooling efficiency

studied the influence of water temperature on the heat transfer coefficient in spray cooling of steel surfaces, and reported that changing the water temperature from 293 K to 353 K caused a change of the Leidenfrost temperature. And the heat transfer coefficient had the highest value at the lowest water temperature (293 K) while the cooling intensity was the lowest at the high coolant temperature (353 K). Also, most of studies have focused on the heat transfer coefficient with respect to Reynold number and surface temperature [8,9]. A lot of researchers studied the effect of Prandtl number on the cooling performance for precise cooling precess with various fluids and cooling types. Li et al. [10] studied the Prandtl number effects and generalized the correlations for confined and submerged jet impingement. They studied the influence of fluid thermophysical properties on the heat transfer from confined and submerged impinging jets for water. They developed valid correlations for heat transfer rate over the range of coolant Prandtl numbers from 0.7 to 25.2. Moallemi and Jang [11] studied the Prandtl number effects on the laminar mixed convection heat transfer. They considered the shear force in a square cavity resulting from the motion of the upper lid combined with buoyancy force due to bottom heating. Shi et al. [12] studied the effects of Prandtl number between 0.7 and 71 on the impinging jet heat transfer under a semi-confined laminar slot jet. Verzicco and Camussi [13] studied the Prandtl number effects by numerical and experimental methods for convective turbulent flow. They studied the Nusselt number dependence on Prandtl number, Reynolds number and Rayleigh number. Durmayaz and Sogut [14] studied the influence of cooling water temperature on the efficiency of a pressurized water reactor nuclear power plant. They found that the thermal efficiency decreased by about 0.12% as the water coolant increase by 1.0 K. Rasti and Jeung [15] estimated the dimensionless correlation for prediction of mass flow rate. The dimensionless correlation and scale analysis were found to be a fairly good way to analyze the tendency for flow characteristics. In addition, the optimization of each influencing factor is required to achieve an optimal efficiency for each system [16–18]. The above discussed papers studied the effects of Prandtl number and Reynolds number on the heat transfer characteristics depending on the variation of feed water temperature. However, the influencing factors such as measurement errors of water temperature, SCT, FCT, water flow density and air cooling effect should be considered for general cooling conditions in plate cooling systems.

Second, the change of plate speed and width should be considered as the influence factors under continuous cooling conditions. In the plate cooling system, the modeling of heat transfer is generally assumed to be one-dimensional because the aspect ration of thickness and width is high. In the production line of cooling equipment, we could find that the deviation of predicted cooling temperature becomes somewhat significant by the change of plate speed and width. Therefore, it is required that the plate speed and width be optimized during the precise cooling process.

Third, the initial temperature distribution and specific heat should be estimated to calculate the calories contained in the plate. The initial temperature distribution can be estimated in natural convection by the Computational Fluid Dynamics (CFD) simulation. In the CFD simulation, the calculation of core temperature is the key issue. In addition, it is difficult to calculate the exact specific heat of plate for each temperature and chemistry composition in various conditions. Therefore, we could refer to data such as specific heats of NIST-JANAF, Eurocode, ISIJ and phase transformation with avrami equation [19–21].

With optimization of cooling conditions, the water flow density could be evaluated for precise water cooling in the accelerated controlled cooling process. Correlations of the effect such as water temperature, plate speed and difference of plate width are applied to control water flow density for plate cooling. The objectives of the present study are to optimize the influence factors during water cooling of high temperature plate by the accelerated control cooling process. The optimization results are compared with those from the experiments over various water temperature range.

2. Experiments

2.1. Plate cooling system

Fig. 1 shows the schematic of the plate cooling system in steel industry. In the plate cooling system, it is very important to predict the FCT of plate and the water cooling time with the primary data such as thickness, SCT, components of chemistry and etc. Generally, the heat transfer model is used to predict the FCT and the water cooling time. When the plate for cooling arrives at the cooling machine, the temperature of plate is usually 1023–1073 K and the thickness range of plate is 8–200 mm. To progress the accelerated controlled cooling, the top surface temperature of plate is measured by the pyrometer before water cooling. The specific cooling conditions such as plate temperature change water cooling time for FCT, water flow density for cooling rate and transporting speed are determined by the cooling model. While the plate is being transported after calculating the set points, it is being cooled by air. After then, the accelerated control cooling is gone through with the cooling water. After finishing the water cooling process, the plate is transported to the scan pyrometer for measuring the top surface temperature. While the plate is being transported after water cooling process, it is being cooled by air again. It is very important to predict the finish temperature and control the water flow precisely.

2.2. Heat transfer model

The principle of energy conservation is very important to the heat transfer model. In the heat transfer model, Fourier's law, Newton's law of cooling and Stefan-Boltzmann's law are applied to the