Hindawi
Mathematical Problems in Engineering
Volume 2017, Article ID 4091342, 6 pages
https://doi.org/10.1155/2017/4091342

Research Article

Optimization of Roller Velocity for Quenching Machine Based on Heat Transfer Mathematical Model

Yunfeng He, Jingkui Zhang, Hua Dong, and Yongqiang Mu

School of Environment and Municipal Engineering, Qingdao University of Technology, Qingdao 266033, China

Correspondence should be addressed to Jingkui Zhang; zk_neu@163.com

Received 28 May 2017; Accepted 22 June 2017; Published 6 August 2017

Academic Editor: Marcello Vasta

During quenching process of steel plate, control parameters are important to product quality. In this work, heat transfer mathematical model has been developed for roller-type quenching machine to predict the temperature field of plate at first, and then an optimization schedule considering quenching technology and equipment limitations is developed firstly based on the heat transfer mathematical model with considering the shortest quenching time. A numerical simulation is performed during optimization process to investigate the effects of roller velocity on the temperature of representative plate. Based on the optimization method, study is also performed for different thickness of plate to obtain the corresponding roller velocity. The results show that the optimized roller velocity can be achieved for the roller-type continuous quenching machine based on the heat transfer mathematical model. With the increasing of plate's thickness, the optimized roller velocity decreases exponentially.

1. Introduction

Quenching is a common manufacturing process to obtain unique service performance properties of metal by controlling the amount and the morphology of microstructural constituents [1]. Roller-type continuous quenching machine is an important device which is commonly used in quenching heat treatment of plate in the iron and steel industry. In recent years, a number of works have been conducted on quenching machine referring to the heat transfer coefficient, critical cooling rate, plate temperature field, flow field, stress distribution, and microstructure distribution. Tang et al. [2], Şimşir and Gür [3], and Huiping et al. [4] simulated the temperature, stress, and microstructure field considering nonlinear material properties using finite element method during the quenching process. Kang and Im [5] established a 3D thermo-elastic-plastic model for plain-carbon steel along with phase transformation to improve the accuracy of numerical simulation. Zhu et al. [6] developed a three-dimensional finite element flow field model of spraying pipe of roller-type quenching machine. Chantasiriwan [7] treated the problem of estimating the transient heat transfer coefficient at the surface of steel bars subjected to quenching using the sequential function specification method. Wang et al. [8] conducted a study on the heat transfer during quenching for plate roller quenching machine. Fu et al. [9] studied the critical cooling rate of plate during quenching. In their study, three types of quenching critical cooling rate models of medium carbon steel, low-carbon steel, and low-alloy construction steel were established with the modified Maynier model, Ei-dis model, and isothermal curve model, respectively.

In recent years, few researches on control parameters' optimization of continuous quenching machine were performed. Wang et al. [10] proposed a calculation method of optimal speed profile for online control system. Lü et al. [11] carried out a calculation model based on coupled metallo-thermo-mechanics theory. With the simulated results, they proposed an optimum quenching scheme. Huiping et al. [12, 13] performed a step function model with respect to optimized technologic parameters during gas quenching process. The heat transfer plays an important role on the quenching heat treatment. However, studies on the optimization of control parameters based on the heat transfer model are few for the continuous quenching machine up to now. Therefore, in this work, the heat transfer mathematical model is developed during quenching process firstly. And then, an optimization method of roller velocity is proposed based on the model considering the quenching technology and water consumption. The optimized roller velocity is also obtained for different plate thickness.

2. Heat Transfer Mathematical Model

Heat transfer during quenching occurs via all possible heat transfer mechanisms, that is, conduction, convection, and radiation. Basically, heat is removed from the surface of the plate by convection to the water on the boundary during quenching process, which results in thermal gradients driving the conduction inside the plate. Because the surface temperature of the plate is higher than 800°C before quenching and higher than 100°C when the plate leaves the high-pressure water injection zone, the form of heat transfer between plate surface and cooling water is big tank boiling convection at the high-pressure water injection zone. The cooling water sprays on the surface of hot plate at constant velocity and angle. The result is that water near the hot plate's surface vaporizes quickly, taking the heat away in the form of latent heat of vaporization. The water away from the steel surface takes away the sensible heat through conduction and convection. When the plate passes the low-pressure water injection zone, the main heat transfer form is forced convection.

2.1. Governing Equations. The transient heat transfer within the plate during quenching can be described mathematically by an appropriate form of Fourier's heat conduction equation (1). The equation can be expressed in its most general form as

$$\rho(T)\,c(T)\,\frac{\partial T(x,y,\tau)}{\partial \tau} = \frac{\partial}{\partial x}\left[\lambda(T)\,\frac{\partial T(x,y,\tau)}{\partial x}\right] + \frac{\partial}{\partial y}\left[\lambda(T)\,\frac{\partial T(x,y,\tau)}{\partial y}\right], \tag{1}$$

where $\lambda(T)$ is the thermal conductivity. $\rho(T)$ is the density of material. $c(T)$ is the constant pressure specific heat, and τ is quenching time.

2.2. Initial and Boundary Conditions. The initial conditions at time $\tau = 0$ can be described as

$$T(x,y,\tau)\big|_{\tau=0} = T_0, \tag{2}$$

where T_0 is the initial temperature of plate.

The boundary conditions are related to the heat transfer between quenching plate and cooling water. The relevant boundary conditions are given as

$$\begin{gathered} q(\tau) = -\lambda(T)\,\frac{\partial T(x,y,\tau)}{\partial n}\bigg|_{\Gamma} = h_{\Sigma}\left(T - T_f\right), \\ 0 < \tau < \tau_{\text{in}}, \quad \text{at } x = 0, w, \\ 0 < \tau < \tau_{\text{in}}, \quad \text{at } y = 0, d, \end{gathered} \tag{3}$$

where q is the heat flux of plate's surface. h_{Σ} is the total heat transfer coefficient including convection and radiation. d and w are the thickness and width of the plate. τ_{in} is the total quenching time. T_f is the water temperature.

The total heat transfer coefficient h_{Σ} is related to the flow flux and velocity of the cooling water, the surface temperature, roughness and emissivity of the plate, and so on. The empirical equation is employed to express the total heat transfer coefficient which is available in [14, 15], and it can be written as

$$h_{\Sigma} = A{q_w}^{B} e^{(CT_s)}, \tag{4}$$

where A, B, and C are regression coefficients. q_w is the flow flux of the cooling water on the plate surface. T_s is the surface temperature of the plate.

2.3. Numerical Method and Codes Validation. The heat transfer mathematical model developed in this work can be used to predict the evolution of temperature during quenching process for the roller-type quenching machine. The governing equation (energy equation) with the boundary conditions is solved by finite volume method (FVM). The FVM is a common method to calculate the heat conduction problem. The codes validation on solving of energy equation has been done by the FVM in our former works which are available in [16, 17].

3. Optimization Method

3.1. Objective Function. The cooling rate of plate during quenching process is determined by the roller velocity under constant water injection condition. Therefore, the roller velocity is the direct factor for quenching. The optimization of roller velocity plays an important role for the quenching machine. In this work, the optimization method of roller velocity is developed on the basis of the heat transfer mathematical model. The shortest quenching time is set as the optimization objective. Because the water injection condition is constant when the roller velocity is optimized, the shortest quenching time corresponds to the least water consumption. The objective function is given as

$$J = \min\left(\frac{L_h + L_l}{v}\right), \tag{5}$$

where L_h and L_l are the length of high-pressure water injection zone and low-pressure water injection zone of the quenching machine. v is the roller velocity.

3.2. Constraints. Constraints mainly include the quenching technology requirements and quenching machine equipment limitations. They can be described as

$$\begin{gathered} V_T \geq V_{T\text{cr}}, \\ T_c \leq 500^{\circ}\text{C}, \\ v_{\min} \leq v \leq v_{\max}, \\ T_c \leq 50^{\circ}\text{C}, \end{gathered} \tag{6}$$

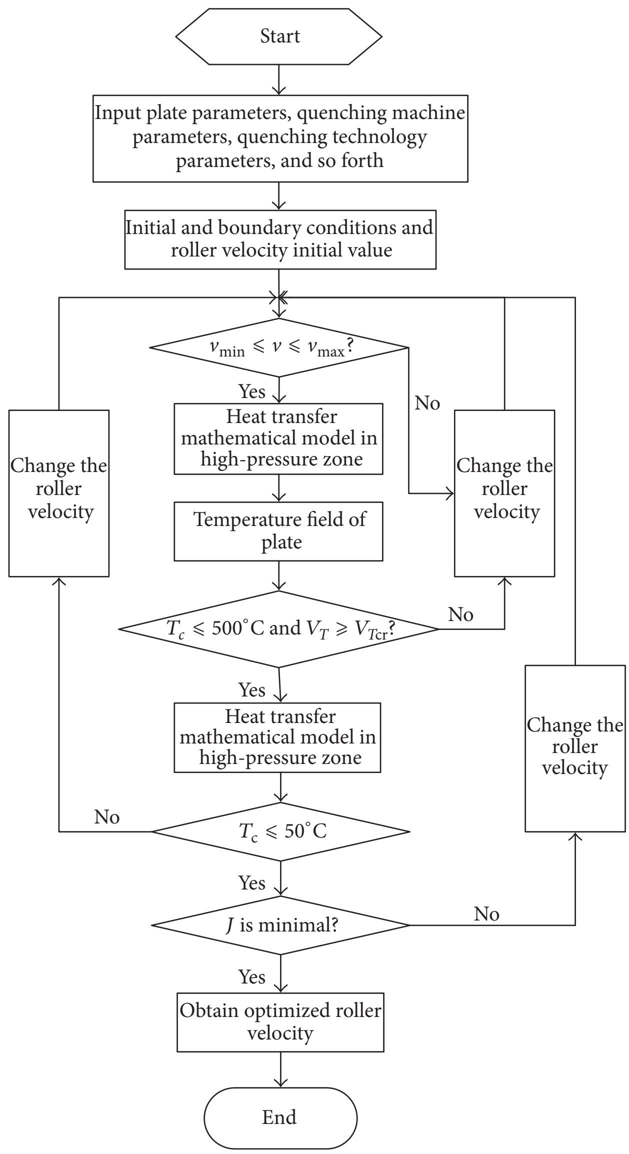

Figure 1: The optimization flow diagram of roller velocity.

where V_T and $V_{T\text{cr}}$ are the actual cooling rate of plate from 800°C to 500°C and critical cooling rate, respectively. $v_{\max}$ and $v_{\min}$ are the maximal velocity and the minimal velocity of roller. T_c is the temperature at the centre of plate.

As the flow diagram shown in Figure 1, the roller velocity is optimized with the objective function in meeting the constraint conditions. Quenching under the optimized roller velocity corresponding to the shortest quenching time is also a process consuming the least water in the case of constant water injection condition.

4. Results and Discussion

A numerical analysis is performed firstly in this work to investigate the effects of roller velocity. Taking the typical plate 50 mm × 2750 mm × 12000 mm as simulated object, the central temperature of plate when it leaves high-pressure water injection zone and low-pressure water injection zone under the initial temperature $T_0 = 940^{\circ}$C is shown in Figure 2. It shows that the central temperature of plate at both positions decreases with decreasing of roller velocity. When the roller velocity decreases to 0.08 m/s, the central cooling rate of plate from 800°C to 500°C reaches 12°C/s, and the central temperatures of plate are 497°C and 29°C when it leaves high-pressure water injection zone and low-pressure water injection zone, respectively. These results meet the quenching technology requirements, so optimized rolled velocity (0.08 m/s) is obtained. During the optimization process, the central temperature of plate when it leaves high-pressure water injection zone decreases slowly when the roller velocity is decreased from 1 m/s to 0.2 m/s and decreases quickly when the roller velocity is lower than 0.2 m/s. The decrease of plate central temperature when it leaves low-pressure water injection zone is faster than that when it

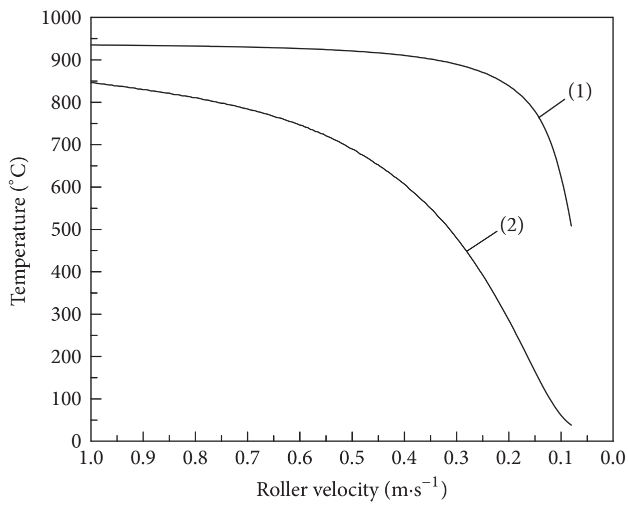

FIGURE 2: The central temperature of the typical plate with the decreasing of roller velocity during optimization.

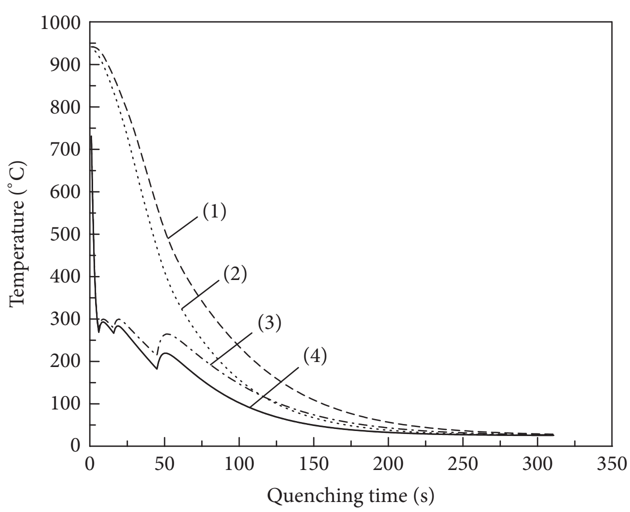

FIGURE 3: The temperature of the typical plate along the quenching time under the optimized roller velocity $v = 0.08$ m/s.

leaves high-pressure water injection zone as the roller velocity is decreased from 1 m/s to 0.2 m/s and is slower than that when it leaves high-pressure water injection zone as the roller velocity is decreased from 0.2 m/s.

The temperature profiles of specified nodes of the typical plate are shown in Figure 3 under the optimized roller velocity (0.08 m/s) during quenching process. Because the heat flux is symmetric, 1/4 section of plate is selected to

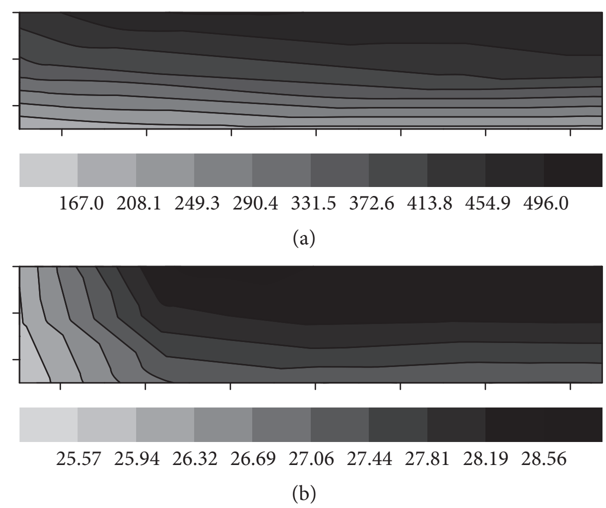

FIGURE 4: The temperature distribution of the typical plate under the optimized roller velocity $v = 0.08$ m/s. (a) When the plate leaves high-pressure water injection zone. (b) When the plate leaves low-pressure water injection zone.

show the temperature distribution as illustrated in Figure 4. The temperature of corner node decreases at the fastest rate, the central temperature of bottom surface is second, the central temperature of side surface is third, and the central temperature of the whole plate decreases at the lowest rate. There are three times temperature fluctuations of corner temperature and the central temperature of bottom surface because of the change of water flux. The temperature difference between bottom surface and central of the plate (line (1) and line (3) in Figure 3) increases at first and then decreases. The temperature difference is larger when the plate leaves high-pressure water injection zone and smaller when the plate leaves low-pressure water injection zone. The maximum temperature difference appears at the high-pressure water injection zone, and the maximum value is about 660°C.

Taking this optimization method in this work, the roller velocity is also optimized for different thickness of plate. The thickness of plate is chosen as $d = 0.01$, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, and 0.08 m to obtain optimized roller velocity and quenching time. The results are given as shown in Figure 5. As seen from the figure, with the increasing of plate's thickness, the roller velocity decreases exponentially. On the contrary, the quenching time increases dramatically. When the thickness of the plate increases from 0.01 m to 0.08 m, the corresponding roller velocity decreases exponentially from 0.97 m/s to 0.034 m/s, and the quenching time changes from 25.5 s to 729.4 s.

5. Conclusions

In this work, the temperature field of the plate is predicted by the heat transfer mathematical method. An optimization schedule is developed firstly with considering quenching technology and equipment limitations based on heat transfer

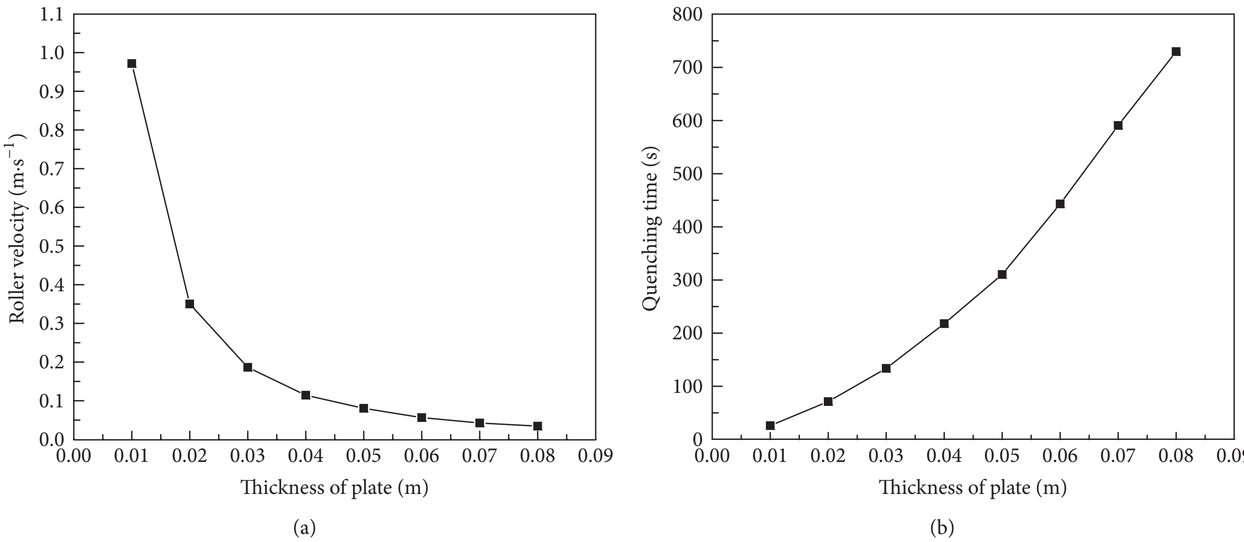

Figure 5: The optimized roller velocity (a) and quenching time (b) for different thickness of plate.

mathematical model. The optimized results of roller velocity are obtained with considering the shortest quenching time. The optimized roller velocity decreases exponentially and the quenching time increases dramatically with the increasing of plate's thickness.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by the Natural Science Foundation of China (NSFC) for young scientists (no. 11402180).

References

[1] W.-M. Gao, D. Fabijanic, T. Hilditch, and L.-X. Kong, "Integrated fluid-thermal-structural numerical analysis for the quenching of metallic components," *Journal of Shanghai Jiaotong University (Science)*, vol. 16, no. 2, pp. 137–140, 2011.

[2] Q. Tang, L.-Q. Pei, and H.-S. Xiao, "Numerical and experimental analysis of quenching process for cam manufacturing," *Journal of Central South University of Technology (English Edition)*, vol. 17, no. 3, pp. 529–536, 2010.

[3] C. Şimşir and C. H. Gür, "3D FEM simulation of steel quenching and investigation of the effect of asymmetric geometry on residual stress distribution," *Journal of Materials Processing Technology*, vol. 207, no. 1-3, pp. 211–221, 2008.

[4] L. Huiping, Z. Guoqun, N. Shanting, and H. Chuanzhen, "FEM simulation of quenching process and experimental verification of simulation results," *Materials Science and Engineering A*, vol. 452-453, pp. 705–714, 2007.

[5] S.-H. Kang and Y.-T. Im, "Three-dimensional thermo-elastic-plastic finite element modeling of quenching process of plain-carbon steel in couple with phase transformation," *International Journal of Mechanical Sciences*, vol. 49, no. 4, pp. 423–439, 2007.

[6] D.-M. Zhu, G.-Y. Liu, S.-J. Zhang, and M.-W. Li, "Flow uniformity of roller-type quenching machine," *Journal of Iron and Steel Research International*, vol. 17, no. 7, pp. 24–27, 2010.

[7] S. Chantasiriwan, "Inverse determination of steady-state heat transfer coefficient," *International Communications in Heat and Mass Transfer*, vol. 27, no. 8, pp. 1155–1164, 2000.

[8] C. Wang, Z.-D. Wang, G. Yuan, D.-Y. Wang, J.-P. Wu, and G.-D. Wang, "Heat transfer during quenching by plate roller quenching machine," *Journal of Iron and Steel Research International*, vol. 20, no. 5, pp. 1–5, 2013.

[9] T.-L. Fu, R.-Q. Wang, Z.-D. Wang, G.-D. Wang, and M.-T. Wang, "Construction and application of quenching critical cooling rate model," *Journal of Iron and Steel Research International*, vol. 17, no. 3, pp. 40–45, 2010.

[10] B.-X. Wang, X.-L. Chen, Y. Tian, Z.-D. Wang, J. Wang, and D.-H. Zhang, "Calculation method of optimal speed profile for hot plate during controlled cooling process," *Journal of Iron and Steel Research International*, vol. 18, no. 5, pp. 38–41, 2011.

[11] C. Lü, L. Zhang, Q. Tai, Q. Zheng, and Z. Qiang, "Numerical simulation and technological parameter optimization for quenching process of a gas turbine compressor disk based on metallo-thermo-mechanics," *Journal of Materials Science & Technology*, vol. 22, no. 6, pp. 860–864, 2006.

[12] L. Huiping, Z. Guoqun, N. Shanting, and L. Yiguo, "Technologic parameter optimization of gas quenching process using response surface method," *Computational Materials Science*, vol. 38, no. 4, pp. 561–570, 2007.

[13] L. Huiping, Z. Guoqun, N. Shanting, and L. Yiguo, "Optimization of technology parameters for the plane-strain component in the process of gas quenching," *Applied Mathematical Modelling*, vol. 32, no. 5, pp. 860–872, 2008.

[14] C. Gong, M. Yu, X. Cai, and G. Wang, "Cooling process control of rolled plate," *Journal of Northeastern University (Natural Science)*, vol. 62, no. 2, pp. 129–132, 2005.

[15] C. Gong, *Research on temperature uniformity for plate controlled cooling process [Ph.D. thesis]*, Northeastern University of China, 2005.

[16] J.-K. Zhang, B.-W. Li, and Z.-M. Hu, "Effects of optical parameters on fluid flow and heat transfer of participating magnetic

fluid," *International Journal of Heat and Mass Transfer*, vol. 59, no. 1, pp. 126–136, 2013.

[17] J.-K. Zhang, B.-W. Li, and Y.-Y. Chen, "Hall effects on natural convection of participating MHD with thermal radiation in a cavity," *International Journal of Heat and Mass Transfer*, vol. 66, pp. 838–843, 2013.