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Effects of ambient temperature and humidity on the controlled cooling of hot-rolled wire rod of steel

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HIGHLIGHTS

- We model the effect of moist air on the cooling process of hot-rolled wire rod.
- The cooling performance of different weather conditions is analyzed and verified.
- High temperature and low humidity decrease the cooling performance of steel.
- Low temperature and high humidity increase the cooling performance of steel.
- The same cooling performance can be achieved via the control of blower.

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ABSTRACT

The effects on the controlled cooling of hot-rolled wire rod of steel at different ambient temperature and humidity have been investigated. The results indicate that the convective heat-transfer coefficients and heat flux increase as humidity increase and temperature decrease. And it results in the increase of cooling rate and the decrease of phase transformation temperature of steel. According to the empirical relationship between the isothermal transformation temperature and experimental results of ultimate tensile strength with steel of SWRH82B and diameter of 12.5 mm, the maximum ultimate tensile strength (UTS) is 1206 MPa at −15 °C and humidity level of 100%, and the minimum UTS is 1139 MPa at 55 °C and humidity level of 0%. The predicted results agree well with the inspection results of industrial trials. And then, some references of the optimal outputs of blower have been provided for stabilizing product quality.

1. Introduction

In hot-rolled steel production processes, controlled cooling after finishing rolling plays an important role on the final microstructure and mechanical properties of product. Stelmor air-cooling process is the most popular controlled cooling process to produce the steel wire with the sizes range from 5 mm to 20 mm. In this process, after passing through the water cooling boxes in which the temperature is reduce down to approximately 800 °C, the rolled wire is placed, by means of laying head, into circle loops on the conveyor, where the forced air cooling is performed by a series of fans below.

Considerable researches have been devoted to research the thermal and microstructural behaviors of steels in controlled cooling process. For instance, Nobari and Serajzadeh [1] developed a mathematical model to predict temperature variations and austenite phase transformation in steel during controlled cooling. Shivpuri and co-workers [2] presented a computational approach to grain size evolution and mechanical properties of hot rolled rod. Yu et al. [3] developed an online Stelmor controlled cooling system for the stabilization of process operation. These numerical models have been successfully applied to controlled cooling process for realizing stable operation and improving product quality. Thus, in industrial practice, with more and more manipulated variables under control, the fact that the product quality varies with season and climate is more and more outstanding.

But up to now, it is no available in the literature to describe the quantitative analysis on the impacts of ambient temperature and humidity upon the cooling process of hot rolled steel. Fortunately, some investigations in the similar treatment were reported. Such as, Brenn and co-workers [4] discussed the effects of ambient conditions on the drying process of liquid coatings on round metal wires. Page et al. [5] reported a model to analyze the effects of ambient

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Nomenclature

b	temperature-dependent constant
Bi	Biot number
C_p	specific heat capacity of moist air
C_{pa}	specific heat capacity of air
C_{ps}	specific heat capacity of steel
C_{pv}	specific heat capacity of water vapor
D	diameter of steel wire
Fo	Fourier number
g	latent heat release rate during phase transformation
h	convection heat-transfer coefficient
k	thermal conductivity of moist air
k_a	thermal conductivity of air
k_s	thermal conductivity of steel
k_v	thermal conductivity of vapor
M_a	average molar mass of air
M_s	transformation-beginning temperature of martensite
M_v	molar mass of water
Nu	Nusselt number
n	temperature-dependent constant
Pr	Prandtl number
p_a	partial pressure of air
p_v	partial pressure of vapor
R	molar gas constant
Re	Reynolds number
r	radial coordinate
T	current temperature
T_i	temperature at ith time step
T_∞	fluid temperature
T_{ref}	reference temperature of fluid
T_{sur}	surroundings temperature
T_{new}	temperature at current step
T_{old}	temperature at previous step
t	current time
t_i	elapsed time until the ith time step
t_i^*	virtual time of at ith time step
Δt_i	time increment at ith time step
u	velocity of moist air flow
X	fraction of transformation
X_i	fraction of transformation at ith time step
x_a	mass fraction of air
x_v	mass fraction of vapor
y_a	mole fraction of air
y_v	mole fraction of vapor
α	constant for specific steel
ε_s	total emissivity
μ	viscosity of moist air
μ_a	viscosity of air
μ_v	viscosity of vapor
ρ	density of moist air
ρ_a	density of air
ρ_s	density of steel
ρ_v	density of vapor
σ_0	Stefan–Boltzman constant
τ_i	incubation time at temperature T_i
φ_{av}, φ_{va}	interaction parameter between air and vapor

conditions during air treatment operations of food. These research results provide application basic for study of the effects of ambient conditions on the controlled cooling of hot-rolled wire rod of steel.

In this work, an integrated model for describing the effects of ambient conditions on the cooling performance of hot-rolled steel wire after rolling is presented. The effects of moist air on heat transfer have been derived from the theoretical and empirical models with the involved ambient conditions, and the results are used to calculate the temperature evolution and phase transformation of high-carbon steel, SWRH82B, by numerical approach. Then the predicted values of ultimate tensile strength are compared with the industrial trials to validate the model. Additionally, the inverse solution of wind speed is also discussed for realizing stable production process under different ambient conditions.

2. Mathematical models

In order to simplify the solution process and focus on the influence of weather, the rolled wire rod cooled on the roller conveyor is assumed as a cylinder in cross flow, which has the same heat-transfer coefficient (HTC) around the surface and has no axial heat conduction. The schematic description of the process is illustrated in Fig. 1. The temperature history of steel wire is solved by heat-transfer model with the corresponding boundary conditions. The boundary conditions vary with the reference temperature due to its influence on the properties of moist air. The microstructure and latent heat of phase transformation at a specific point are determined by its time–temperature paths in isothermal transformation diagram.

2.1. Models of heat transfer

Based on the following assumptions: (1) uniform initial temperature, (2) circular cross-sectional shape with the same boundary conditions, (3) no longitudinal temperature gradient, the heat-transfer process within steel wire in Stelmor line can be described by one-dimensional decisive differential equation [3]:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rk_s\frac{\partial T}{\partial r}\right) + g = \rho_s C_{ps}\frac{\partial T}{\partial t} \tag{1}$$

The boundary conditions can be described as follows.

At the center,

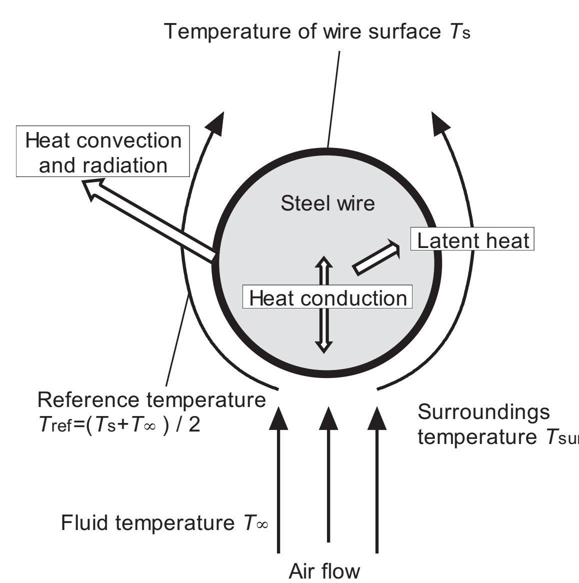

Fig. 1. Schematic of a cylinder in cross flow.