

Model to Calculate the Cooling Rate along the Strip Length Direction in Hot Strip Mill

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Abstract. The basic theory of cooling after rolling was introduced firstly. The cooling process of strip steel was summarized as three typical cases. On the basis of Time-Velocity-Distance (TVD) curve, the cooling time model in each case was calculated. By means of the measured finishing delivery temperature, coiling temperature and the Stefan-Boltzmann law, the temperature drop was calculated. Combining the cooling time with the temperature drop, the calculating model for cooling rate along the strip length direction was developed in hot strip mill. The achievement was applied to a hot strip plant successfully. With the help of the results of cooling rate, process parameters were set up and controlled accurately and conveniently.

1. Introduction

Cooling rate is one of the most crucial parameter in the production of hot rolled strip [1-3]. For the purpose of obtaining the appropriate microstructure and mechanical properties, researchers carried out a large of basic studies on the cooling procedures to find the optimal cooling rate for different steels[4-6]. Hu found the best cooling rate for a high strength steel which the strength and toughness was well-balanced [7]. Jiang pointed out that the cooling rate was the most important factor affecting the mechanical and showed a great influence on the hardness of the pipeline steel[8]. As we all known that the main intention of the basic research is to provide guidance for the production. In the hot strip rolling line [9], the calculation of cooling rate is treated as an essential process. However, the trend of increasing strip velocity accompanies by the adjusting of cooling water makes it a difficult process to calculate the cooling rate exactly along the strip length direction[10]. In this work, the cooling system arrangement was presented firstly. On the basis of coiling temperature control system, the model to calculate the water cooling time was discussed in detail, which followed by the calculating of cooling rate. What's more, the application results were shown in the last part.

2. Cooling System Arrangement

The steel slab, reheated in the furnace, goes through the rough rolling and finish rolling processes, and then turns into hundreds of meters strip before entering a cooling system (CS). The CS consists of run-out table (ROT) and laminar cooling headers. The ROT is located between the finish rolling and coiler. The laminar cooling headers are arranged above and beneath the ROT. The laminar cooling headers can be divided into two functional parts: the main cooling zone and the fine cooling zone. The main cooling zone is grouped by 18 banks, and each bank consists of 4 top headers and 4 bottom headers. The fine cooling zone is grouped by 2 banks, and each bank consists of 8 top headers and 8 bottom headers. The flow rate of top header in the main cooling zone is 120m³/h while the bottom header is 130m³/h. The flow rate of cooling headers in the fine zone is the half of the headers in the main zone. Every cooling header can be turned on or off via pneumatic switches respectively. The arrangement of cooling equipment is shown in Fig.1.

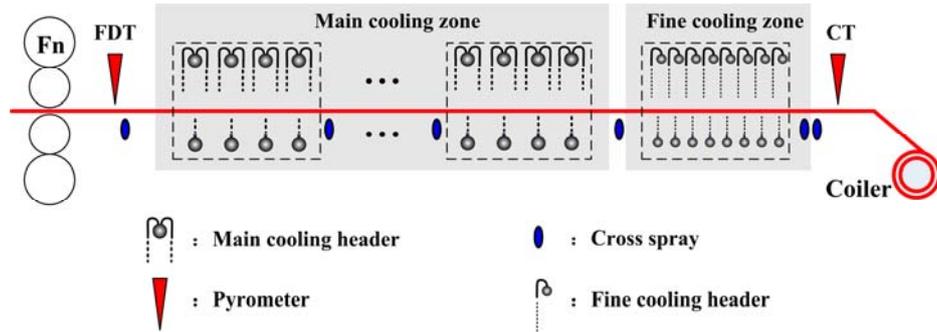


Figure 1. Arrangement of the cooling equipment

3. Model for Cooling RATE Calculating

Cooling rate indicates the temperature drop per unit time, and the mathematical formula is concluded as follows:

$$V_c = \frac{\Delta t}{\tau} \quad (1)$$

Where, V_c is the cooling rate of steel, Δt is the temperature drop of steel during the water cooling, τ is the water cooling time. Equation (1) shows that the temperature drop and the cooling time must be obtained for the calculating of cooling rate.

3.1 Basic Theory of Cooling Control after Rolling.

The action scope of cooling control system is the area locating between finishing delivery temperature (FDT) pyrometer and coiling temperature (CT) pyrometer, which is divided into an equal length cooling sections. According to the section length, strip is divided into a quantity of samples which is shown in Fig.2.

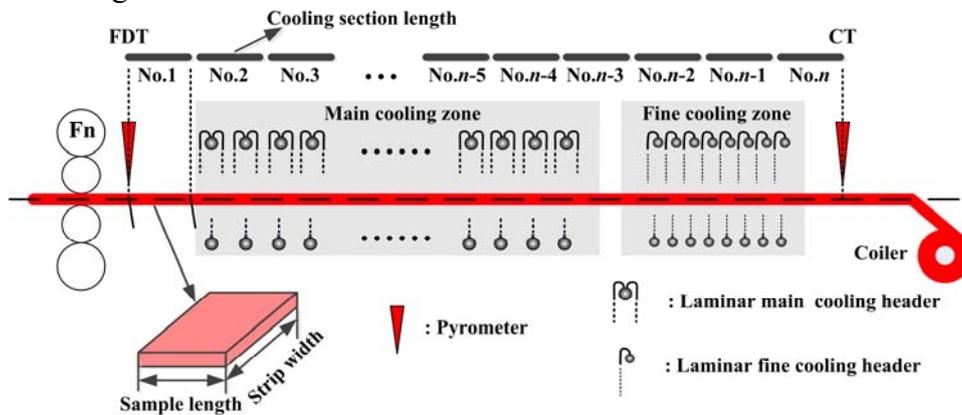


Figure 2. Basic thought of cooling process

As soon as a new sample of strip is detected by instruments at the delivery of the finishing mill, measured value of parameters, such as FDT, velocity, acceleration, thickness etc. are available. According the measured and predicted parameters, the cooling control system calculates the temperature drop of the new sample in every cooling section. The iterative method is employed to calculate the required water distribution, which indicates the numbers and location of the working header, to meet the targeted CT, and then the optimal cooling pattern is obtained.

3.2 Calculating of Cooling Rate.

According to the discussion above, the water cooling time is the key parameter to obtain the cooling rate. To compensate for the temperature decreasing of the transfer bar, the rolling velocity is risen gradually in the hot mill production. The Time-Velocity-Distance (TVD) curve is used to describe the strip velocity variation.

Because the velocity of strip fluctuates in real time, the TVD curve was refreshed by the actual history of velocity in time[11], and the velocity in every cooling section for every sample can be obtained exactly. The calculation result of TVD is shown in Table 1.

Table.1. Calculation result of TVD

Sample Number	Parameter	Cooling Section				
		1	2	3	4	5
1	Entry Velocity	2.71	2.76	2.8	2.84	2.89
	Exit Velocity	2.76	2.81	2.85	2.88	2.93
	Running Time	0.85	0.83	0.82	0.81	0.8
2	Entry Velocity	2.76	2.8	2.84	2.89	2.93
	Exit Velocity	2.81	2.85	2.88	2.93	2.97
	Running Time	0.83	0.82	0.81	0.8	0.79
3	Entry Velocity	2.8	2.84	2.89	2.93	2.97
	Exit Velocity	2.85	2.88	2.93	2.97	3.01
	Running Time	0.82	0.81	0.8	0.79	0.78
4	Entry Velocity	2.84	2.89	2.93	2.97	3.01
	Exit Velocity	2.88	2.93	2.97	3.01	3.04
	Running Time	0.81	0.8	0.79	0.78	0.77
5	Entry Velocity	2.89	2.93	2.97	3.01	3.04
	Exit Velocity	2.93	2.97	3.01	3.04	3.06
	Running Time	0.8	0.79	0.78	0.77	0.76

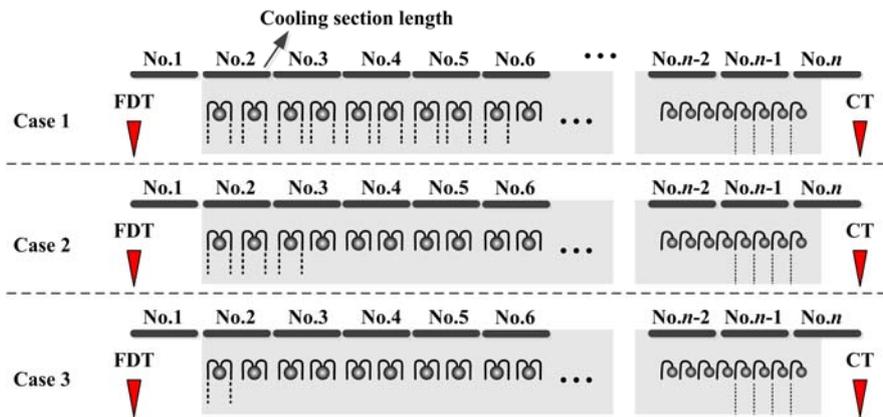


Figure 3. The typical cooling process

Table 1 shows that the entry velocity, exit velocity and running time in every cooling section for every sample are calculated. What's more, the parameters of sample 2 in cooling section 1 are equal to that of sample 1 in cooling section 2, which indicates that the calculating results faultlessly match the actual. Here, it needs to be pointed out that we treat it as a uniformly accelerated process in every cooling section.

Every cooling header and cooling section is numbered. The position, which contains the start and end location for every cooling section, and the position for every header is pre-configured in database. During the strip cooling process, we can generalize three typical cases, and be shown as Fig.3.

As case 1 shown in Fig.3, there are more than three cooling section with cooling header working. The corresponding cooling section number of the first working header and the last working header are named S_s' and S_e respectively. The water cooling time is consisted of the running time in S_s , S_e and in the section between S_s' and S_e . The running time in the section between S_s' and S_e , named a_m , can be obtained by TVD curve as shown in Table 1.

The running time in section S_s' is calculated as follows.

$$a_s = \frac{(V_{se}^2 - V_{ss}^2)}{2 \times L_s} \quad (2)$$

$$V_{ssh} = \sqrt{V_{se}^2 - 2 \times a_s \cdot (p_{se} - p_{hs})} \quad (3)$$

$$\tau_s = \frac{2 \times (p_{se} - p_{hs})}{V_{ssh} + V_{se}} \quad (4)$$

where, as is the acceleration in section Ss, Vase is the exit velocity in Ss, Voss is the entry velocity in Ss, Ls is the section length, Vs. is the velocity under the first working header, pose is the ending position of section Ss, this is the position of the first working header, as is the cooling time in section Ss.

The running time in section Ss is calculated as follows.

$$a_e = \frac{(V_{ee}^2 - V_{es}^2)}{2 \times L_s} \tag{5}$$

$$V_{eeh} = \sqrt{V_{es}^2 + 2 \times a_e \cdot (p_{he} - p_{es})} \tag{6}$$

$$\tau_e = \frac{2 \times (p_{he} - p_{es})}{V_{es} + V_{eeh}} \tag{7}$$

Where, are is the acceleration in section Se, Vie is the exit velocity in Se, Vest is the entry velocity in Se, Veer is the velocity under the last working header, phi is the position of the last working header, pose is the starting position of section Se, he is the cooling time in section Se.

$$\tau = \tau_s + \tau_m + \tau_e \tag{8}$$

Where τ is the cooling time in case 1 as shown in Fig.4.

As case 2 shown in Fig.3, it is obvious that there is no am, and the cooling time can be calculated according to case 1. As case 3 shown in Fig.3, the working headers are locating in one cooling section, which is named section S. The running time in section S is calculated as follows.

$$a = \frac{(V_e^2 - V_s^2)}{2 \times L_s} \tag{9}$$

$$V_{sh} = \sqrt{V_s^2 + 2 \times a \cdot (p_{hs} - p_s)} \tag{10}$$

$$V_{eh} = \sqrt{V_e^2 - 2 \times a \cdot (p_e - p_{he})} \tag{11}$$

$$\tau = \frac{2 \times (p_{he} - p_{hs})}{V_{sh} + V_{eh}} \tag{12}$$

where, a is the acceleration in section S, Vet is the exit velocity in S, Vs is the entry velocity in S, VT is the velocity under the starting working header, Vet is the velocity under the last working header, PS is the starting position of section S, pen is the ending position of section S, τ is the cooling time in section S.

By means of the measured FDT and CT, the temperature drop for every sample can be calculated during the whole process of cooling. The temperature drop during the air cooling can be calculated by the Stefan-Boltzmann law, and then the temperature drop of the water cooling will be obtained. The cooling rate naturally can be obtained by equation (1).

4. Field Application

The achievement was successfully applied to a hot strip plant. Fig.5 shows the calculating results of cooling rate along the strip length direction.

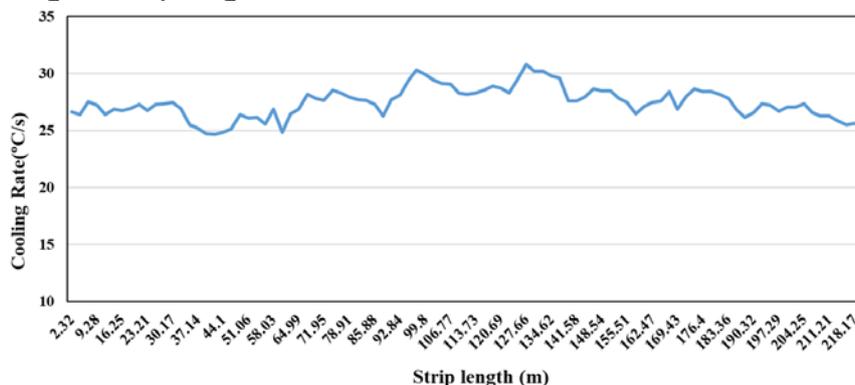


Figure 4. The calculating results of cooling rate

With the help of the results of cooling rate, process parameters were set up and controlled accurately and conveniently.

5. Conclusion

In the hot strip mill, the cooling process of the strip steel was summarized as three typical cases. On the basis of Time-Velocity-Distance (TVD) curve, the cooling time model in each case was calculated. By means of the measured finishing delivery temperature, coiling temperature and the Stefan-Boltzmann law, the temperature drop was calculated. Combining the cooling time with the temperature drop, the calculating model for cooling rate along the strip length direction was developed. The achievement was successfully applied to a hot strip plant, and the process parameters were set up and controlled accurately and conveniently.

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