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Improvement of Cooling Process for Strip in Annealing & Coating Line

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The cooling parameters for each cooling zone in the Annealing & Coating Line (ACL) are the key factors for the magnetic properties and the shape of electrical steel strip. A finite difference numerical method was used to simulate the jet cooling process of a movable steel strip in the cooling zone. The cooling parameters of the cooling air temperature and flow rate were calculated through a programming design in which the two objective parameters, the mean temperature difference and the average cooling rate, are minimized. The upper chamber nozzles of odd number were displaced 60mm outward, and the lower chamber nozzles of even number were displaced 60mm outward. Strip temperature is more uniform after the cooling chamber position was revised. When the technology was applied to the CSC Annealing & Coating Line, it showed a satisfactory result with the iron loss and necking deformation conforming to the quality control standard.

1. INTRODUCTION

The cooling zones of the Annealing & Coating Line consists of 2 Cooling Tube sub-Zones (CTZ), 7 Slow Jet Cooling sub-zones (SJC), and 10 Fast Jet Cooling sub-zones (FJC). The cooling parameters for each cooling zone in the Annealing & Coating Line (ACL) are the key factors for the magnetic properties and the shape of the electrical steel strip. Therefore, the technique to cool the strip is important. During the period of hot run, the strip showed deformation in the middle areas along the width direction. In additions, the strip deformation was too large to suit the EI-shape that it was divided into.

Although the respective cooling rates for the slow jet cooling zone and the fast jet cooling zone are smaller than 10°C/s and 35°C/s to fit the metallurgy standard, the grain size, iron loss and necking deformation have not conformed to the quality control standard. The reason for the deformation is that the cooling rates for the sub cooling zones are not controlled well.

The pyrometers to measure the strip temperature are located between two adjacent sub cooling zones. The cooling rate is calculated based on the inlet strip temperature, outlet strip temperature and cooling time. Meanwhile, the cooling air temperature and flow rate should be consistent with the strip temperature to avoid the cooling of strip being too fast. Thus, the cooling rate of a strip in the cooling zone is important to product quality and should be controlled well.

2. EXPERIMENTAL METHOD

The streamline of jet nozzle impingement is shown in Figure 1. The cooling effect on the strip is calculated by the Nusselt number. Equations (1) and (2) represent the relationship between the nozzle geometry and Nusselt number[1,2].

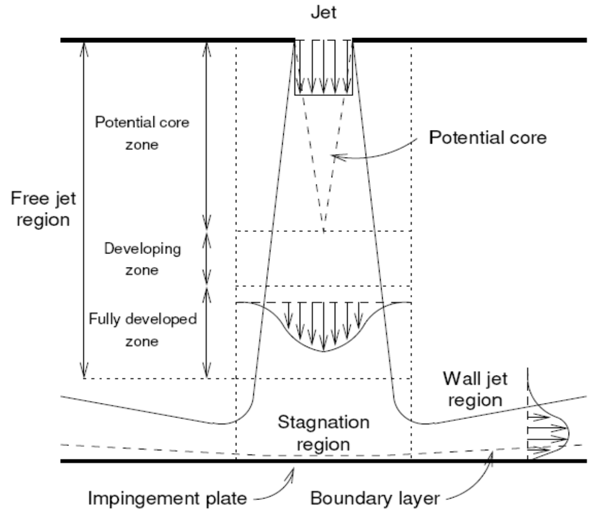


Fig. 1. Impingement flow.

$$Nu_{stag} = 0.641 Re^{0.566} (H / D)^{-0.078} \quad (1)$$

$$Nu_{average} = 0.993 Re^{0.625} (H / D)^{-0.625} (s / D)^{-0.375} \quad (2)$$

Where H is the nozzle height, D is the nozzle diameter, s is the distance between two adjacent nozzles, Nu_{stag} is the Nusselt number in stagnation region, and $Nu_{average}$ is the Nusselt number in the impingement area.

Figure 2 shows the impingement cooling on the strip surface. The finite difference method is adopted to model the cooling process. There are 7 nodes on the strip surface between two adjacent nozzles. The internal energy of the strip is a function of enthalpy and strip temperature. The time derivative of internal energy is defined as Equation (3).

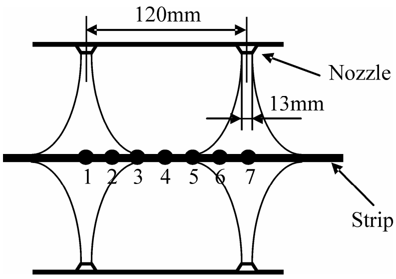


Fig. 2. Diagram of the nozzle position relative to impingement effect.

$$\frac{\Delta E}{\Delta \tau} = \rho c \Delta V \frac{T_i^{k+1} - T_i^k}{\Delta \tau} \quad (3)$$

Where ΔE means strip energy increment, ΔV means cell volume, $\Delta \tau$ mean time step, i means position index, k means time index, ρ means strip density, and c means strip specific heat. $C_i = \rho_i c_i \Delta V_i$, then energy balance at each node is described as Equation (4).

$$\sum_j \frac{T_j^k - T_i^k}{R_{ij}} = C_i \frac{T_i^{k+1} - T_i^k}{\Delta \tau} \quad (4)$$

Where R_{ij} is the heat resistant between node i and adjacent nodes(R_{i+} 、 R_{i-} and R_{∞}), represented by Equations (5) and (6).

j is upstream node→

$$R_{i+} = R_{i-} = \frac{\Delta x}{k(\Delta W \cdot t)} \quad (5)$$

j is convection circumstance→

$$R_{\infty} = \frac{1}{h(\Delta W \cdot \Delta x)} \quad (6)$$

where k is strip thermal conductivity, h means heat transfer coefficient, ΔW means unit strip length, Δx means distance between adjacent nodes, and t means strip thickness. By substituting Equations (1) and (2) into Equation (4), the strip temperature distribution between two nozzle can be found.

3. RESULTS AND DISCUSSION

The temperature uniformity of the strip is a key factor to flatness and iron loss in the strip. In this study, a finite difference numerical method was utilized to investigate the cooling effects on strip for different parameters of nozzle diameter, cooling chamber position, and to determine cooling parameters on strip cooling rate and temperature difference.

3.1 The Cooling Effect of Nozzle Diameter on Strip Temperature

The strip temperature distributions for different nozzle diameters are analyzed. The simulation conditions for cooling parameters are 930°C of strip exit temperature at soaking zone, 112mpm (meter per minute) of strip speed, 0.013m nozzle diameter in the slow jet cooling zones, and 0.017m nozzle diameter in the fast jet cooling zones.

The temperature uniformity of strip should kept be in a reasonable range for different strip temperature to prevent strip deformation. Thus, it is important to reduce the mean temperature difference at a higher strip temperature and to decrease a strip temperature at a higher mean temperature difference. Table 1 shows the simulation results for #1 zone and #2 zone in the slow jet cooling zone(SJC) with a larger nozzle diameter of 0.032m. The strip mean temperature difference is reduced from 0.68~1.16°C /mm to 0.13~0.25°C /mm, implying that the temperature uniformity of strip is significantly improved. In addition, the cooling rate of the strip can be reduced from 7.86~10.15°C /s to 3.41~5.12°C /s by increasing the cooling fan valve opening from 20~30% to 100%. The simulation results show that a larger nozzle size and more open cooling fan valve reduces the strip deformation caused by a higher mean temperature difference when the strip enters the slow jet cooling zones.

Table 2 shows the simulation results for #3 zone and #4 zone in slow jet cooling zone with a larger nozzle diameter of 0.032m. The strip mean temperature difference is reduced from 1.29~1.32°C/mm to 0.36°C/mm and the cooling rate is reduced 50%. Even when the cooling fan is fully open, i.e. the valve opening is 100%, the cooling rate with the larger nozzle diameter is smaller than with a smaller nozzle diameter. The stronger cooling fan also makes the strip temperature increase slightly by 2.82°C at the entrance of the fast jet cooling zone.

Table 1 Comparison for the large nozzle diameter of SJC #1 Zone, #2 Zone

Nozzle Diameter(mm)	13		32		32	
Zone	#1	#2	#1	#2	#1	#2
Air Temperature(°C)	693	655	693	655	693	655
Valve Opening (%)	20	30	20	30	100	100
Temperature Difference (°C/mm)	0.68	1.16	0.13	0.25	0.25	0.37
Cooling Rate(°C/s)	7.86	10.15	3.41	5.12	8.53	8.95

Table 2 Comparison for the large nozzle diameter of SJC #3 Zone, #4 Zone

Nozzle Diameter(mm)	13		32		32	
Zone	#3	#4	#3	#4	#3	#4
Air Temperature(°C)	640	609	640	609	640	609
Valve Opening (%)	40	40	40	40	100	100
Temperature Difference (°C/mm)	1.29	1.32	0.36	0.36	0.40	0.42
Cooling Rate(°C/s)	9.78	9.36	4.69	5.22	7.86	8.03
Entry Strip Temperature at FJC	579.81		588.64		582.63	

Table 3 Comparison for the large nozzle diameter of FJC #1 Zone, #2 Zone

Nozzle Diameter(mm)	13		32		32	
Zone	#1	#2	#1	#2	#1	#2
Air Temperature(°C)	281	236	281	236	281	236
Valve Opening (%)	80	80	80	80	100	100
Temperature Difference (℃/mm)	2.57	2.70	1.32	1.27	1.33	1.27
Cooling Rate(°C/s)	54.95	42.70	32.42	30.54	36.81	33.62
Strip Temperature at the Exit Cooling Zone (°C)	111.08		115.39		114.82	

Table 3 shows the simulation results for #1 zone and #2 zone in the fast jet cooling zone with the larger nozzle diameter of 0.032m. The strip mean temperature difference is reduced to 46% and the cooling rate is reduced to 70%. However, the larger nozzle makes the strip temperature increase by about 4°C at the exit of the fast jet cooling zone.

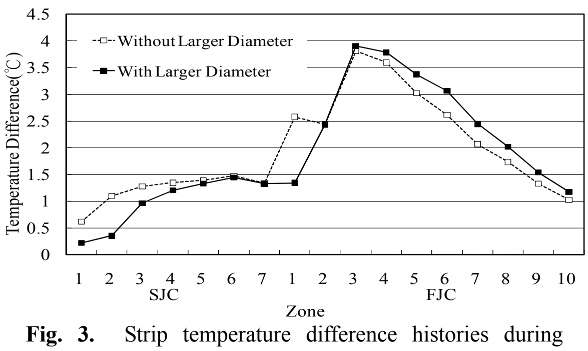


Fig. 3. Strip temperature difference histories during cooling process with and without larger nozzle diameter of SJC #1, #2 Zone and FJC #1 Zone.

Figure 3 shows the strip mean temperature difference with the larger nozzle diameter at #1 zone and #2 zone of the slow jet cooling zone and at #1 zone of the fast jet cooling zone. The solid line represents the results with the larger nozzle diameter, and the dotted line represents the results with the standard nozzle diameter. The valve opening of the cooling fan is shown in Table 1 and Table 3. The strip temperature uniformity with a lager nozzle diameter is better than that with a small nozzle diameter. Besides, the strip flatness is improved by using a larger nozzle diameter. The results show that the strip mean temperature difference is reduced from 1.33°C/mm to 2.57°C/mm.

The higher strip mean temperature difference with a higher strip temperature could cause the deformation. Thus, it is important to control a larger strip mean temperature difference with a lower strip temperature. When we chose a larger nozzle diameter for the fast jet cooling zones, the location with the most severe mean temperature difference changed from #1 zone to #2 zone. The strip temperature was reduced to 509.13°C at the inlet of #2 zone and the average strip temperature was 461.05°C. The cooling rate of the strip was reduced by using a larger nozzle diameter at #1 zone of fast jet cooling zone. As a result, the strip temperature increased by 2.7°C, from 111.08°C to 113.78°C, using the larger nozzle diameters at #1 zone and #2 zone of the slow jet cooling zone and at #1 zone of the fast jet cooling zone.

Table 4 Comparison for strip temperature behavior of different scheme

Schemes 1-6 for different cooling zone with nozzle diameter of 32mm			Average Strip Temperature difference at SJC (°C/mm)	Strip Temperature at Higher Temperature Difference (°C)	Max Strip Temperature Difference (°C/mm)	Strip Temperature at the Exit Cooling Zone (°C)
		No Change(SJC:13mm, FJC:17mm)	1.21	527.46	3.74	111.08
Case	1	SJC #1 Zone, #2 Zone	0.96	527.46	3.74	111.08
	2	SJC #1 Zone, #2 Zone, #3 Zone, #4 Zone	0.74	529.46	3.75	111.12
	3	SJC #1 Zone, #2 Zone, FJC #1 Zone	0.96	461.05	3.87	113.78
	4	SJC #1 Zone, #2 Zone, FJC #1 Zone, #2 Zone	0.96	392.55	3.91	114.82
	5	SJC #1 Zone, #2 Zone, #3 Zone, #4 Zone, FJC #1 Zone	0.74	462.83	3.90	113.84
	6	SJC #1 Zone, #2 Zone, #3 Zone, #4 Zone, FJC #1 Zone, #2 Zone	0.74	393.87	3.94	114.89

In this study, the different schemes of using nozzle diameter of 32mm were analyzed. Table 4 shows the more larger nozzles in slow jet cooling zone, the less strip mean temperature difference. Besides, the location with the maximum strip mean temperature difference is changing from the location with higher strip temperature to the location with lower strip temperature. The strip deformation could be reduced with a larger nozzle diameter, and the outlet strip temperature increased with a larger nozzle diameter.

3.2 The Cooling Effect of Cooling Chamber Position on Strip Temperature

Figure 4 shows the strip temperature distribution between two adjacent cooling nozzles. The temperature gradients for the strip temperature from zone 1 to zone 7 are 0.40°C/mm, 0.65°C/mm, 0.84°C/mm, 0.91°C/mm, 0.97°C/mm, 1.20°C/mm and 1.54°C/mm, respectively.

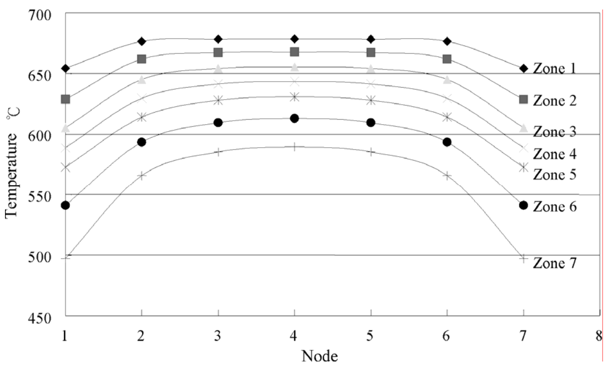


Fig. 4. Strip temperature distribution between two adjacent nozzles.

Figure 5 shows the cooling effect of the cooling chamber on strip temperature. The air temperature and strip outlet temperature is kept the same and the strip speed is increased up to 130mpm. The numerical results show valve openings of cooling fan for zone 1 to zone 7 are 20%, 20%, 25%, 30%, 40%, 30% and 30%, respectively. Figure 6 shows the cooling effect on strip temperature after the cooling chamber positions are revised.

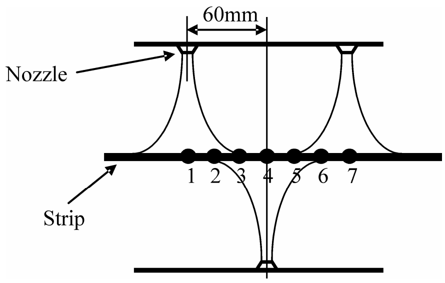


Fig. 5. Diagram of the revised nozzle position.

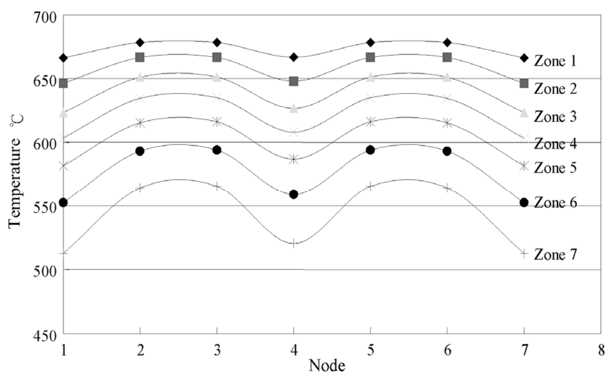
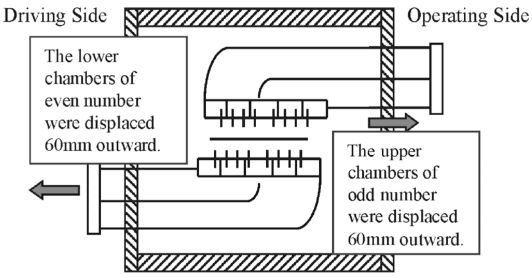


Fig. 6. Strip temperature distribution for the revised nozzle position.

Figure 7 shows the method of the revised nozzle position. The upper chambers of odd number were displaced 60mm outward, and the lower chambers of even number were displaced 60mm outward. Strip temperature is more uniform after the cooling chamber position is revised, the results are shown in Fig. 8.



Cross-section of the revised chamber

Fig. 7. Method of the revised nozzle position.

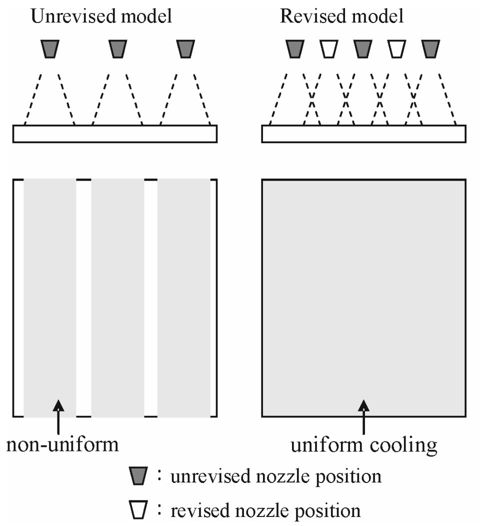


Fig. 8. Cooling effect of the nozzle.

3.3 Cooling Process Parameters Setting

The cooling parameters for each cooling zone in the Annealing & Coating Line (ACL) are the key factors to the magnetic properties and the shape of the electrical steel strip. In this paper, a finite difference numerical method is used for simulating the jet cooling process of a movable steel strip in the cooling zone. The cooling parameters of the cooling air temperature and flow rate are calculated through a programming design in which two objective parameters, the mean temperature difference and the average cooling rate, are minimized. The cooling air temperature and the flow rate for each cooling zone are calculated using the strip speed, the strip size, the mechanical properties, the inlet temperature and the outlet temperature of the steel strip. Figure 9 shows the strip cooling rate during the cooling process. The cooling rate of strip is slow in the CTZ before tuning the cooling parameters, leading to the cooling rate of the strip being fast in SJC. The high temperature difference leads to deformation and high iron loss. After tuning the cooling parameters, the cooling rate of strip is fast in CTZ. The deformation is better and iron loss is low. When this technology is applied to the Annealing & Coating Line, it shows a satisfactory result with the iron loss and necking deformation conforming to the quality control standard.

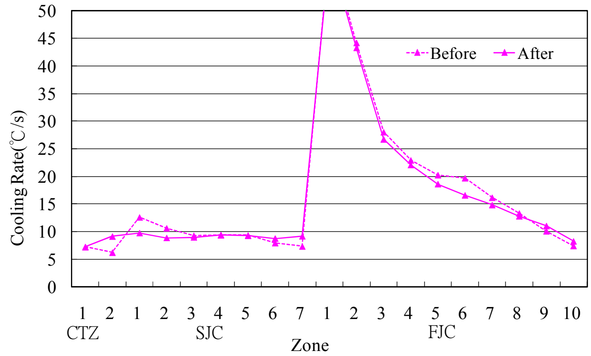


Fig. 9. Strip cooling rate during cooling process.

4. CONCLUSIONS

In this study, the different schemes of using larger nozzle diameters were analyzed. It shows that when there are more and larger nozzles in the slow jet cooling zone, the strip mean temperature difference is reduced. Besides, the location with maximum strip mean temperature difference is changed from that with higher strip temperature to that with lower strip temperature. A larger nozzle diameter could reduce strip deformation, though the outlet strip temperature would increase.

The upper chamber nozzles of odd number were displaced 60mm outward, the lower chamber nozzles of even number were displaced 60mm outward. Strip temperature is more uniform after the cooling chamber position is revised.

A finite difference numerical method was used for simulating the jet cooling process of a movable steel strip in the cooling zone. The cooling parameters of cooling air temperature and flow rate are calculated through a programming design in which the two objective parameters, the mean temperature difference and the average cooling rate, are minimized. When the technology was applied to the Annealing & Coating Line, it showed a satisfactory result with the iron loss and necking deformation conforming to the quality control standard.

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