Numerical simulation of flow, temperature and phase fields in U71Mn rail-head quenching process

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Abstract

With the sustainable and fast development of Chinese economy, the volume of railway freight was increasing, and which promoted the train load and speed continue improving, in order to meet the needs of high speed and over loading trains' running, heavy and seamless steel rail has increasingly widely used Heat-treatment was emphasized for its important role to qualify the products of heavy rail. And air-cooling quenching was one of the widely used heating process methods. Air-jet is a very vital instrument in quenching by air-cooling. At present, the international community has been widely used air-cooled quenching, most quenching production lines of domestic converted into wind cold quenching line. It is necessary to simulate the inner and outer flow-field of air-jet. In this paper, by means of computational fluid dynamics soft system Fluent to establish the geometric model of heavy rail, analysis the distribution of the internal and external flow field about air-jet centre cross section and the three sections were in parallel with it. Then through setting surface heat transfer coefficient of air-cooling, numerical simulation of temperature field in the cooling process of heavy rail. Finally, the phase changing temperature of steel U71Mn was got based on its CCT curves. With the cooling curves of several key points, the cooling rate at phase transition point was calculated. By comparing with every microstructure's critical cooling rate, the final cooling microstructure was predicted. Relative tests showed that the prediction was reasonable. It is significantly valuable for parameters' selection in heavy rail's technical operation.

Keywords: temperature field, flow field, phase field, air-cooling, heavy rail.

1 Introduction

As economy of our country was developing at a high speed, the railway transport was required to develop deeply. The use of heavy rail can meet the demand of large amount of load; therefore, heat-treatment of rail end was becoming more and more emphasized. Quench cooling type was one of the most important treatments in heavy rail heat-treatments, and it was also a major factor influencing quenching quality. The type of atomize-cool and air-cool are widely used in the world now. Because atomize-cool quench treatment was strictly required in controlling and sensitive to rail surface state, there was sometimes something wrong with the quality. While the velocity of air-cool treatment waves little, what's more, air-cool treatment was not sensitive to rail surface state, influenced little by artificial factor that ensure the quality of quench. The experts and scholars of domestic and foreign made many studies on quenching process. Australia's I. Elkatatny [1] by the method of computational fluid mechanics, using the software of H13 mold temperature of high pressure gas field simulation, the results obtained and the experimental results are analysed, and obtained the certain research results. The United States of America Z. Li [2] using response surface method, surface during high-pressure gas quenching heat transfer coefficient are obtained through calculation, and then for the properties of materials after high pressure gas quenching are analysed. Computational fluid dynamics method of gas quenching process of work piece was simulated, and the establishment of the three-dimensional unsteady model of vacuum high-pressure gas quenching furnace on the platform of FLUENT [3], the distribution of flow field and temperature field of work piece in furnace simulation, effects of cylindrical work piece during quenching gas type, gas pressure and speed to the cooling rate was simulated, and the simulation of quenching process [4], provides a theoretical basis for the optimization of gas quenching technology. Using the finite difference principle and experimental study of a detailed analysis of the nonlinear heat conduction problem in high pressure gas quenching steel [5-6], and then studied the synthetic surface heat transfer coefficient of the relevant issues, and consider the influence on the results of the phase transition. This paper was that by means of computational fluid dynamics soft system Fluent to establish the geometric model of heavy rail, simulated the distribution of the flow field, temperature field respectively on the rail air-cooled quenching, and

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made predict of the rail's structure, which make scientific guidance in the actual production for the rail.

2 The establishment of numerical model

Air-jet device was a symmetric structure, as shown in Figure 1. 5 Air inlets with 10mm diameter, the diameter of inner hole was 0.5mm, distance was 3mm between two adjacent holes.

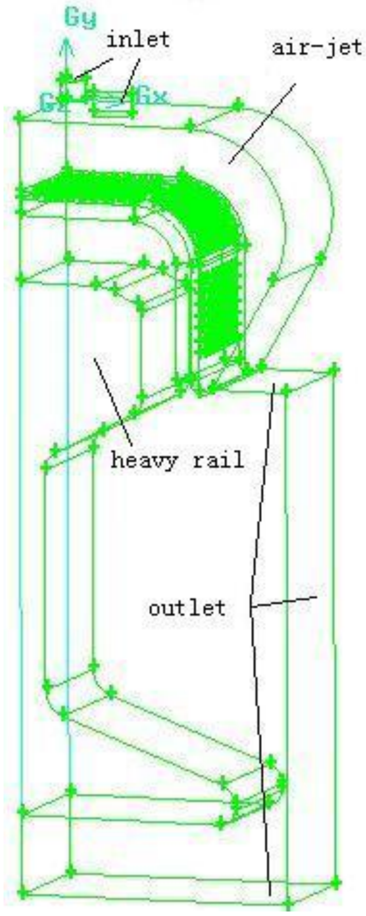

FIGURE 1 Configuration of the model

Use the Gambit that the pre-processing software of Fluent to create model. Because the model was a structure of the axial symmetry, in modelling only took 1/4 model to research. As shown in Figure 1, the lower model of air-jet was heavy rail, the heavy rail was surrounded by external flow-field, air inlet took one circle and one quarter, the air outlet was three walls. Take the an unstructured tetrahedral to mesh generation, the grid number was 2,070,000, because the diameter of small hole was too litter, the area which close to the porous panel will be block processing, in order to reduce the grid number. The wall condition of the nozzle entrance was pressure entrance, the values was pressure of gas supply, took 0.4 MPa in calculate, entrance temperature was 320 K , the export interface was pressure outlet, the pressure value was zero, and the temperature was $320K$; the interface of heavy rail and the flow field with the wall type, which use the way of convection, the heat transfer coefficient was $780W/(m^2 \cdot K)$. The reference pressure was $101325Pa$, temperature was $320K$. The researched model of this paper was 3D model, selected pressure solver, used the steady-state solver to calculate fluid, used the unsteady solver to calculate the temperature field, turbulence model took the standard k-ε turbulence model. Considering the calculation of temperature field relates to surface heat transfer, so the flow of gas to the ideal gas. U71Mn steel material density was $7800kg/(m^3)$, which Thermal conductivity of steel and the mean specific heat at constant pressure were set in the material properties with linear way respectively, the coefficient as shown in Table 2 and Table 1, the surface heat transfer coefficient of air-cooling was $780W/(m^2 \cdot K)$, and set the initial temperature of solid materials was $900^{\circ}C$ [7].

Thermal conductivity of U71Mn with the change of temperature was shown in Table 1.

TABLE 1Thermal conductivity of U71Mn

$T(^{\circ}C)$	100	200	300	400	500
$\lambda(W/(m\cdot K))$	40.24	37.68	35.08	32.94	30.84
$T(^{\circ}C)$	600	700	7752	800	900
$\lambda(W/(m\cdot K))$	28.86	26	28.59	26.19	24.88

Mean specific heat at constant pressure C_P, the unit is $J/(kg\cdot^{\circ}C)$. Mean specific heat at constant pressure of U71Mn steel as shown in Table 2.

TABLE 2 Mean specific heat at constant pressure of the U71Mn

$T(^{\circ}C)$	100	200	300	400	500
$C_p(J/(kg\cdot^{\circ}C))$	478	487	505	533	579
$T(^{\circ}C)$	600	700	752	800	900
$C_p(J/(kg\cdot^{\circ}C))$	650	772	1037	760	623

When solved the surface heat transfer coefficient of gas cooling, usually use the temperature data of work-piece that measured by experiment, and then through the finite volume difference method， nonlinear estimation method to solve. The nonlinear relationship between the surface heat transfer coefficient and surface temperature is shown in figure 2. The heat transfer coefficient was in the range of $200 \sim 1500W/(m^2 \cdot K)$. The coefficient in $270 \sim 720^{\circ}C$ range is basically unchanged. A heat convection transfer was the main way in air-cooled [8].

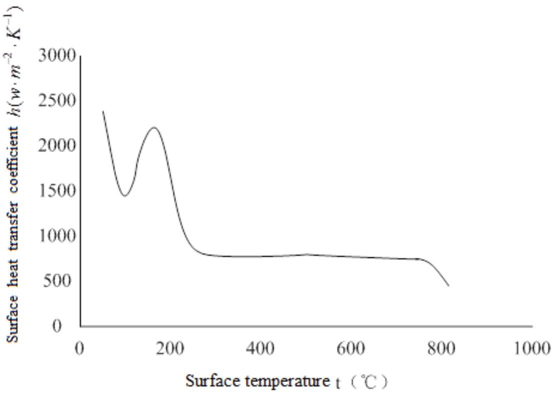

FIGURE 2 Surface heat transfer coefficient of air-cooling

As can be seen from Figure 2, for temperature from $300^{\circ}C$ to $750^{\circ}C$, a heat transfer coefficient was basically stable at around $800W/(m^2 \cdot K)$. So in this temperature range, select $800W/(m^2 \cdot K)$ for heat transfer coefficient, while at $760 \sim 810^{\circ}C$ temperature, heat transfer coefficient as a curve, selected of 4 key points numerical in the curve, in turn (745,800), (760,750), (800,500), (810,450), then, took four coordinates into the MATLAB use the method of least squares to calculate the expression of the curve. This expression was as follows:

$$y = 0.0012x^3 - 2.8x^2 + 2201x - 570505, \qquad (1)$$

and, as far as data of blow $300^{\circ}C$, the software does not involve the calculation till the temperature $300^{\circ}C$, therefore not be considered. The heat transfer coefficient remains numerical value at $810^{\circ}C$ for the $810 \sim 900^{\circ}C$ just took $450W/(m^2 \cdot K)$, which the heat transfer coefficient data only test to $810^{\circ}C$ in experiment. Therefore, the expressions of heat transfer coefficient changed to this:

$$\begin{cases} y = 800, 300 \le x \le 745 \\ y = 0.0012x^3 - 2.8x^2 + 2201x - 570505, 745 \le x \le 810 \\ y = 450, 810 \le x \le 900 \end{cases}. \qquad (2)$$

3 The simulation analysis and results of flow field

The inner and outer flow field distribution at cross section Z=0 of the model and the streamlines distribution of flow field, as shown in Figures 3 and 4.

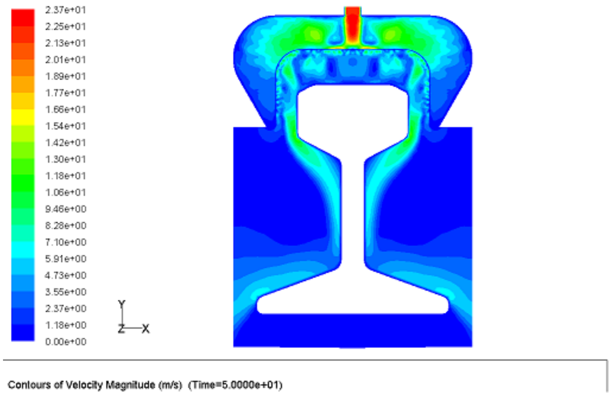

FIGURE 3 Flow field of Z=0 section

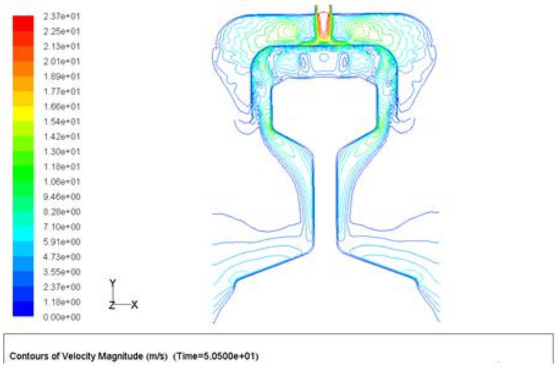

FIGURE 4 Streamlines pattern of Z=0 section

From Figures 3 and 4 can be seen, that the upper wind speed of air jet nozzle is higher, the wind speed of the holes of horizontal porous panel was much higher than it of the vertical porous panel, the speed of rail web was higher, flow field around heavy rail head was distributed uniformity.

Inner flow field and streamline pattern of X=0 section of air jet nozzle are shown in Fig.5 and Fig.6:

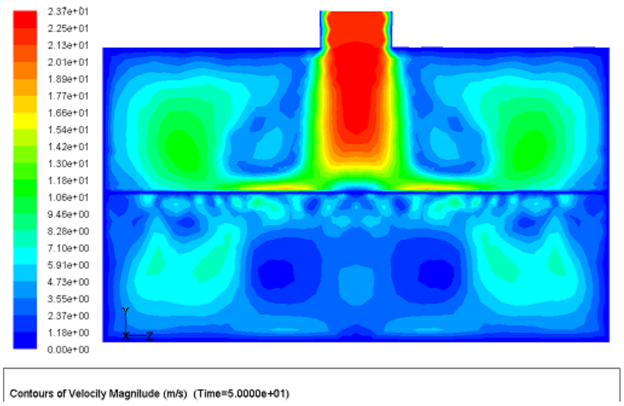

FIGURE 5 Inner flow field of X=0 section of air jet nozzle

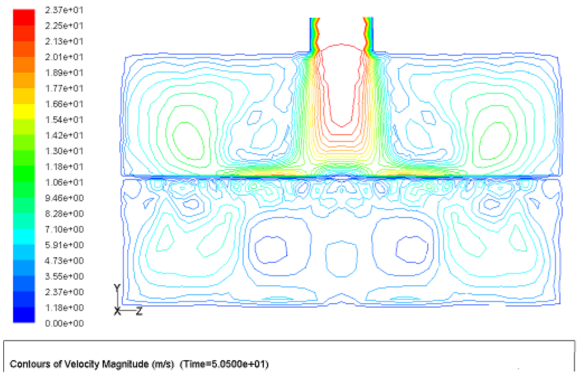

FIGURE 6 Inner streamlines pattern of X=0 section of air jet nozzle

As shown in Figures 5 and 6, when the high speed air from air inlet enters the porous plate, because the small size of the hole, most of the airflow through holes cannot flow out, but by the panel barrier to the surrounding flow, causing air flow rates of holes from the section centre 20mm significantly reduced.

The contents of the above, have studied the flow field of the centre section for a more comprehensive understanding of the flow of information, it was necessary for comparative study on flow field of each section parallel to the centre section. The following selects three sections parallel to cross section (z=0) to analysis.

The flow field of sections from the centre plane are as follows: 10mm, 20mm, 30mm.

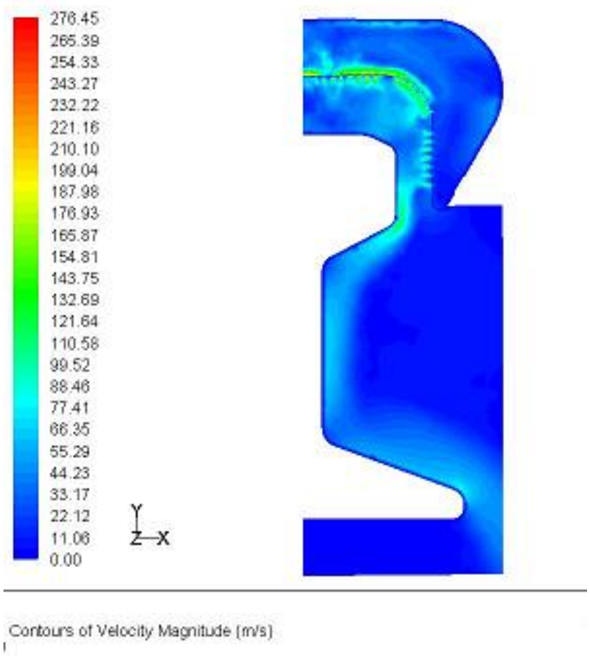

FIGURE 7 The flow field about sections of z=10mm

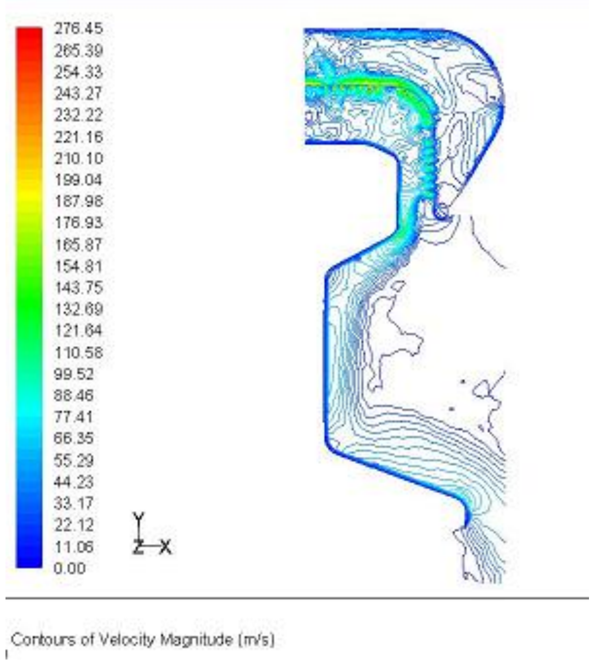

FIGURE 8 Streamlines pattern of Z=10mm

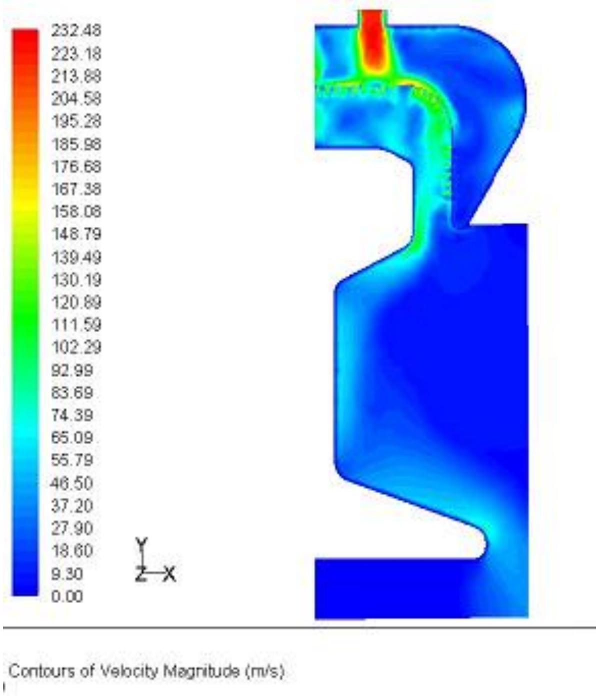

FIGURE 9 The flow field about sections of z=20mm

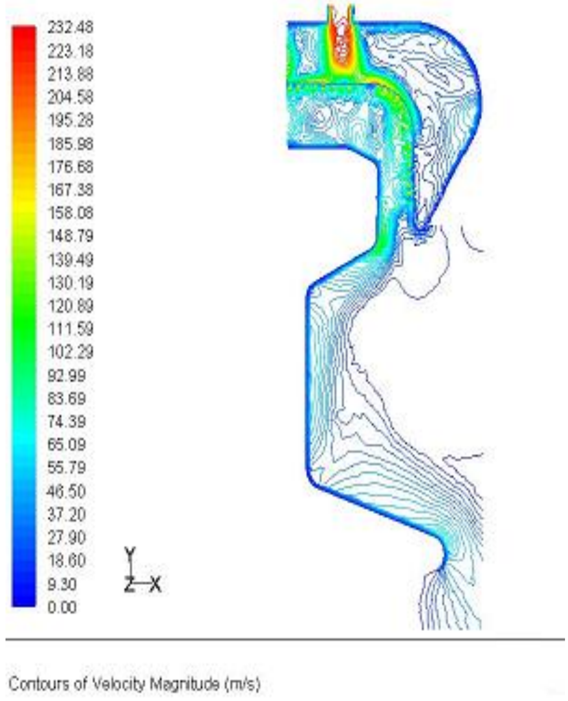

FIGURE 10 Streamlines pattern of Z=20mm

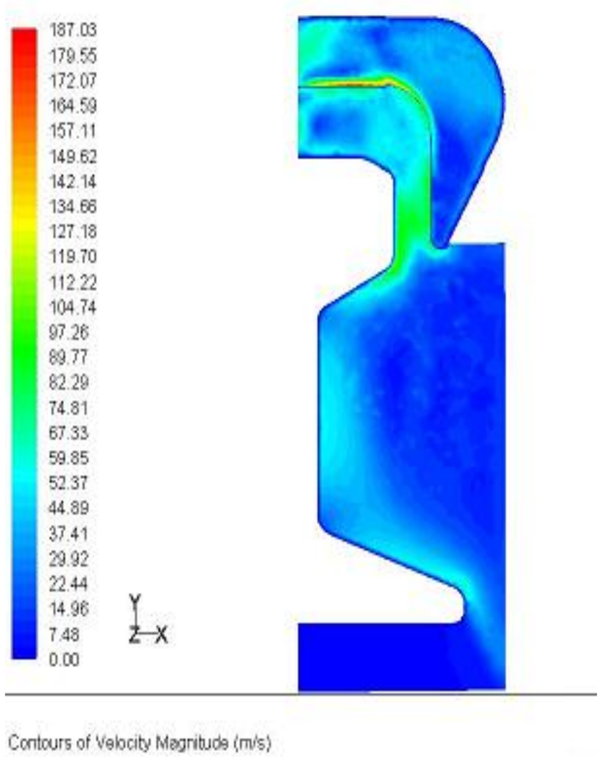

FIGURE 11 The flow field about sections of z=30mm

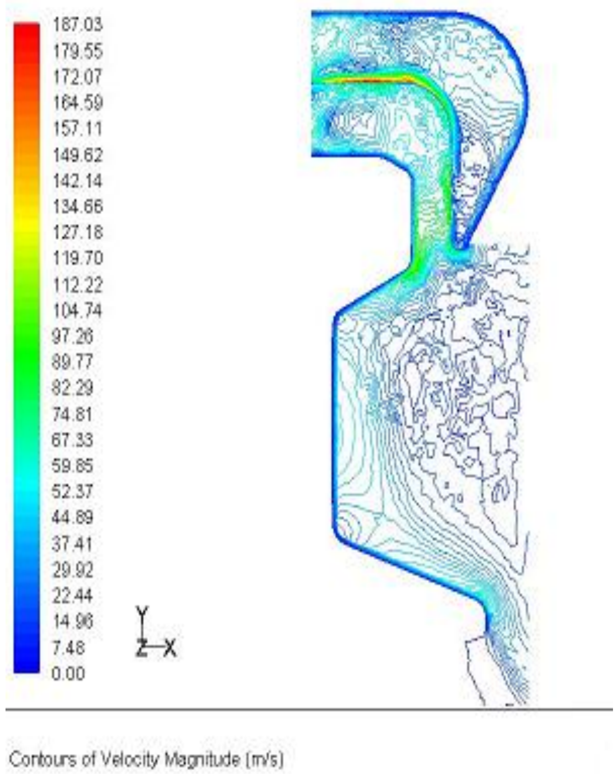

FIGURE 12 Streamlines pattern of Z=30mm

Figures 7-12 show, that the airflow become very irregular (because of the 5air inlet position). There are also differences in each cross section and longitudinal section of the flow field. Generally speaking, a flow rate near the area of air inlet was high, away from the area of the air inlet was low. Especially the flow rate of the two sharp corners area of air jet nozzle was very low. There are some rules in general about flow field near the region outside the air jet nozzle. An airflow from the porous plate in the horizontal direction directly flows to the surface of heavy rail airflow from the porous plate in the vertical direction flows to the area between the mandible and the maxilla of heavy rail in certain inclination. Then ten it flows to the rail web of heavy rail, and finally - into the rail foot [9].

4 The simulation analysis and results of temperature field

The Figure 13 of temperature field about heavy rail was shown on the air-cooled 50s moment.

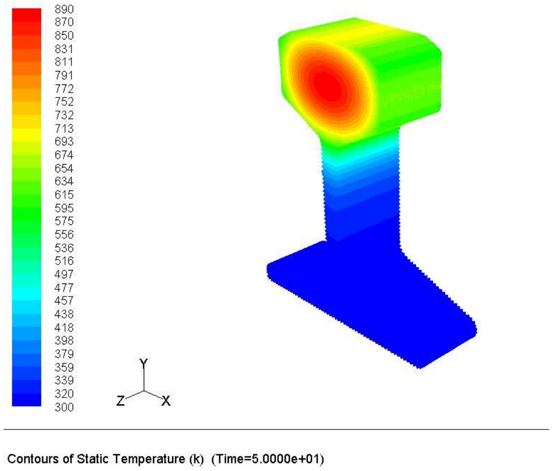

FIGURE 13 Temperature figure for heavy rail on air-cooled 50s moment

The following rules can be drawn: the part of highest temperature was located in the central of the rail head, temperature approach to 890 K that was 617$^{\circ}C$. The temperature of rail head decreases gradually from outside to inside, and the lowest temperature was 540 K , namely 267$^{\circ}C$; At the part of rail waist, the temperature reduces gradually from top to bottom, and the top temperature was 500 K , the equivalent of 227$^{\circ}C$; The foot part, the temperature was basically 300 K , temperature of 27$^{\circ}C$.

The cooling rate of some key points of heavy rail end was analysed for statistics [10], and these key points should be selected according Figure 14, setting greater distance than 10mm between two points on the tread surface and greater distance than 6mm between two points in the part of the maxilla. The selected points are marked in figure.

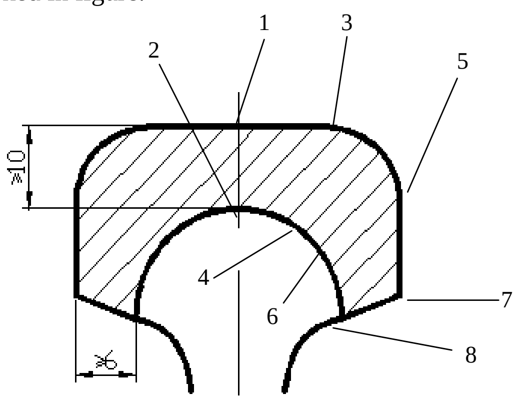

FIGURE 14 Hardening layer of rail end section and node locations

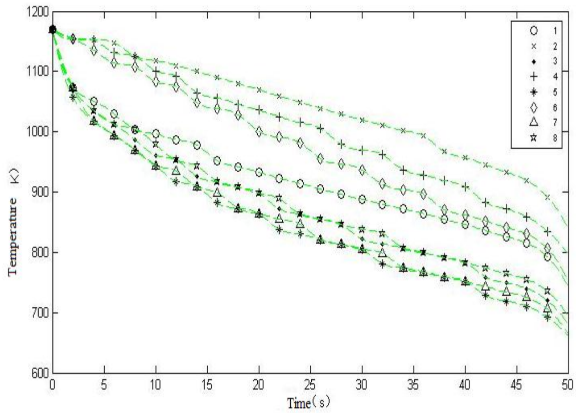

FIGURE 15 Temperature curve of hardened layer as time

The surface temperature distribution of the whole rail accords with the test results relevant temperature field.

5 The microstructure field prediction

Pearlite was formed by the community of ferrite and cementite from the eutectoid transformation of austenite. The morphology of pearlite was the layered composite material through the lamellae overlapping of ferrite slices and cementite slices, also called as lamellar pearlite. The process of air-cooling was in order to get the pearlite to enhance the comprehensive performance of heavy rail-head. The pearlite can be obtained as long as the hot heavy rail of formed austenite cools according to a certain cooling rate. The most appropriate cooling rate can not only obtain desired tissues, but also can make the internal stress to the minimum. Quench method of air-cooling can satisfy this condition [11].

Steel has three main critical cooling rates at the phase transition point:

1) The critical quench cooling rate of martensite v_k $^{o}C/h$: if the cooling speed was higher than v_k , the quenching steel will become the marten site;
2) The critical quench cooling rate of bainite v_3 : if the cooling speed was higher than v_3 , the quenching steel will become the bainite;
3) The critical annealing cooling rate of ferrite - pearlite v_1 : if the cooling speed was less than v_1 , the steel will become into ferrite and pearlite.

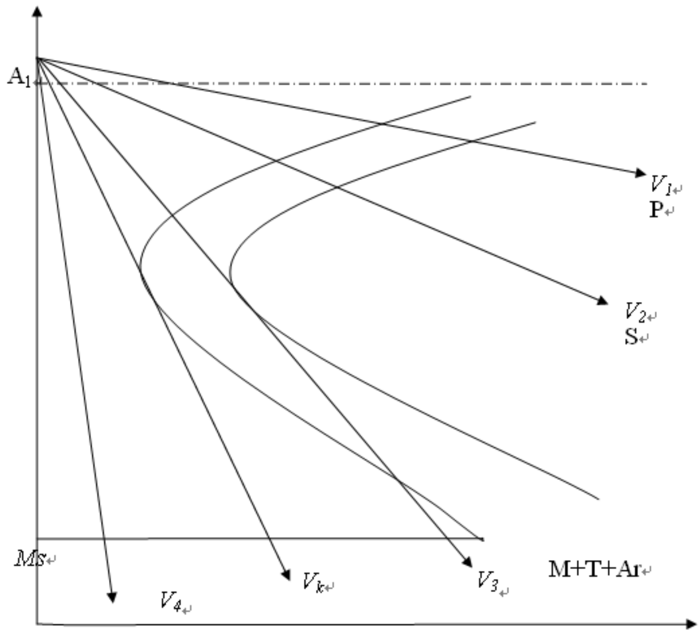

FIGURE 16 Austenite Isothermal Transformation Curve (C curve)

Studying on classification of more than 600 CCT curves was summarized by P Maynie r later on in the industry, the calculation of critical cooling rate equations was summed up:

$$\lg v_k = 9.81-(4.62\times C+1.05\times Mn+0.54\times Ni+0.5\times Cr+0.66\times Mo+0.00183\times P_A \quad (3)$$

$$\lg v_3 = 10.17-(3.8\times C+1.07\times Mn+0.7\times Ni+0.57\times Cr+1.58\times Mo+0.0032\times P_A \quad (4)$$

$$\lg v_1 = 6.36-(0.43\times C+0.49\times Mn+0.78\times Ni+0.27\times Cr+0.38\times Mo+2.0\times\sqrt{Mo}0.0019\times P_A \quad (5)$$

Among them: Mn, Ni, Cr - the mass fraction of various alloy elements in steel body, unit 1%, P_A -- austenitising condition, unit $^{\circ}C/h$, numerical calculation was as follows [12]:

$$P_A = \left|\frac{1}{T_A} - \frac{nR}{\Delta H}\lg\frac{t}{to}\right| \quad (6)$$

The critical cooling rate of the tissues was calculated, as shown in table 3.

TABLE 3 The critical cooling rate of various tissues of steel

$\lg v_3$	$\lg v_1$	$v_3(^{\circ}C/s)$	$v_1(^{\circ}C/s)$
5.03	5.74	29.85	7.16

The temperature falling curve of eight nodes was shown in the Figure 17.

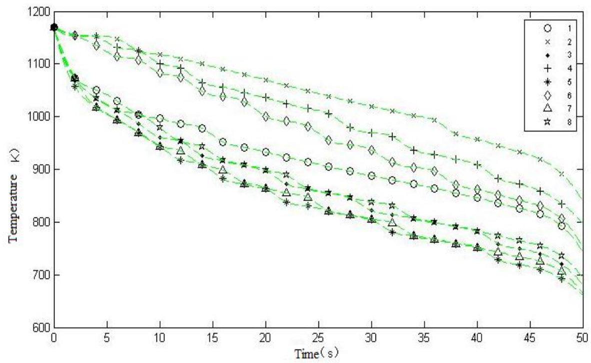

FIGURE 17 Temperature curve of hardened layer as time

According to the analysis of transition curve, phase change cooling process of the U71Mn in the beginning of the temperature was about $700^{\circ}C$, therefore, the three spline interpolation method was adopted to fit the points in $700^{\circ}C$ continuous cooling curves with MATLAB software [13]. Because the temperature unit uses the Kelvin temperature in this software, so the phase transformation starting temperature was $973K$ and the curve equations of following points are obtained in the vicinity of the $973K$:

Node 1: $T = -x^3 + 2.6x^2 - 6.6x + 978$

Node 2: $T = -x^3 + 1.2x^2 - 5.2x + 993$

Node 3: $T = x^3 - 1.4x^2 - 10.4x + 987$

Node 4: $T = -0.7x^3 + 4.2x^2 - 5.8x + 979$

Node 5: $T = -0.1x^2 - 11.8x + 994$

Node 6: $T = -1.8x^3 + 3.3x^2 - 5.5x + 981$

Node 7: $T = -0.1x^3 - 0.8x^2 - 10x + 994$

Node 8: $T = 0.6x^3 - 4.1x^2 - 6.9x + 1004$

Based on the equation above followed by the time derivative in turn, equation of each node in the cooling rate of $700^\circ C$ can be obtained as following:

Node 1: $v = -3x^2 + 5.2x - 6.6$

Node 2: $v = -3x^2 + 2.4x - 5.2$

Node 3: $v = 3x^2 - 2.8x - 10.6$

Node 4: $v = -2.1x^2 + 8.4x - 5.8$

Node 5: $v = -0.2x - 11.8$

Node 6: $v = -2.4x^2 + 6.6x - 5.5$

Node 7: $v = -0.3x^2 - 1.6x - 10$

Node 8: $v = 1.8x^2 - 8.2x - 6.9$

According to the method of three spline interpolation, setting x=0, the cooling speed of each node in the $700^\circ C$ moment can be obtained.

TABLE 4 Nodes at $700^\circ C$ require the time and cooling rate

Node	The time of reach $700^\circ C$	The cooling rate $^\circ C/s$
1	15	6.6
2	38	5.2
3	9	10.6
4	30	5.8
5	8	11.8
6	25	5.5
7	8	10
8	10	6.9

According to the prediction of the quenching process model in section 4, compared the cooling rate of each node at $700^\circ C$ in table 4 with the critical cooling rate of each node in the table 1, quenching microstructure of each node can be predicted: for the cooling rate of region lower than $7.16^\circ C/s$, where nodes 1, 2, 4, 6, 8 lie, it was predicted that the quenching microstructure of these areas was fully pearlite; for the cooling rate of region between $7.16^\circ C/s$ and $29.85^\circ C/s$, where nodes 3, 5, 7 lie, it was predicted that the quenching microstructure of these areas was not fully pearlite, containing a small amount of ferrite in tissue.

6 Conclusions

In this paper, with using the Fluent software built the model of heavy rail in air-cooled quenching process, to simulate the inner and external flow field of air-jet, obtained the rule of flow field of external of air-jet, and then through setting the surface heat transfer coefficient of air-cooled, obtain the temperature field distribution of heavy rail in air-cooled quenching of 50s. That's provided certain reference value for the adjustment of parameters, which the influence of air-jet cooling. Finally, according to the CCT curves and empirical formulae, to gather statistics of the cooling rate of key nodes in hardened layer, the cooling curves were fitted with MATLAB software, and then the cooling rate at $700^\circ C$ was obtained by derivation and compared with critical speed of the quenching structure, then forecasted the final quenching structure. According to the related experimental results show that it was accurate prediction. The whole simulation results were accurate. Through this method to study the dimension of parameters about air-jet and predict the quenching structure, which it was better way to guide the process improvement in the production [14].

Acknowledgments

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