

# Calculation and Analysis of Temperature Distribution in Hot Rolling Strip

**Kaixiang Peng**

Key Laboratory for Advanced Control of Iron and Steel Process, School of Automation and Electrical Engineering, University of Science and Technology of Beijing  
No. 30 Xueyuan Road, Haidian District, Beijing 100083, China  
e-mail: kaixiang@ustb.edu.cn

## **Abstract**

*Modern steel grades require constant and reproducible production conditions both in the hot strip mill and in the cooling section to achieve constant material properties along the entire strip length and from strip to strip. Calculation of the temperature in final rolling process always utilizes factors such as the work piece's inner organizational structure, plastic deformation, and its variations of properties and so on, also as well as the physical parameters such as gauge, shape, etc. In this paper, a finite element model is constructed for the temperature field in a rolling process. The temperature field of strip steel is modeled with a 3-D finite element analysis (FEA) structure, simultaneously considering the distribution of the work roll temperature. Then the distribution of field is simulated numerically. From the model, the temperature contours can be obtained by analysis of the temperature distribution of contact area. At the same time, the distribution of temperature in any position at any time can be acquired. These efforts provide the reliable parameters for the later finishing temperature and shape control.*

**Keywords:** Hot rolling strip, Temperature distribution, Finite element, Temperature field

**Copyright © 2013 Universitas Ahmad Dahlan. All rights reserved.**

## **1. Introduction**

Hot rolling of steel is a very complex process. In order to produce a strip of metal with uniform mechanical properties and hence a uniform microstructure both hot rolling and the cooling conditions on finishing mill must be carefully controlled [1], [2].

Generally, a hot strip mill includes seven finishing mills, which reduce the thickness of the transfer bar down to the gauge required by the customer or the next process. The rolling speed is set to allow the last stand to perform the final reduction at the finishing temperature, between 820° and 900 , specified to reach certain mechanical properties. A finishing temperature for each product is specified and mill control system will adjust the speed of the final finishing mill stand based on its temperature and the extent to which the bar is expected to cool as it makes its way through each stand, in order to allow the strip exiting the finishing stands to meet the target temperature. A pyrometer placed after the last stand updates the finishing mill's computer models and allows for the addition of this temperature to strip quality records.

Calculation and analysis of the strip temperature distribution during hot rolling has always been emphasized by roll mill designers and manufacturers. There have been many studies about the prediction of temperature distribution in a slab during the hot rolling process. Hollander [3] developed a one-dimensional finite difference model to control the temperature distribution during hot strip rolling. Devadas and Samarasekara [4] have predicted temperature distribution in hot strip rolled metal, as well as in the work roll. The temperature variations in work-rolls have been considered in a few papers [5], [6], [7]. Sluzalec [5] has utilized a two-dimensional finite element method to predict temperature distribution during hot rolling and Teseng et al. [6] have estimated temperature variations in the work-roll, in order to evaluate the thermal stress distribution in the rolls. The temperature distribution and metal flow during rough rolling were predicted by Chen et al [8] utilizing two-dimensional finite element and finite difference methods. Mei et al. [9] developed a finite element method to calculate the temperature distribution in hot rolling process. The heat transfer coefficients of air cooling, water cooling and thermal resistance between work roll and strip were analyzed.

As detailed above, calculation of temperature distribution during hot rolling has been studied by many investigators and there is a large body of literature on this subject. However, few of these studies have considered the distribution of temperature in width direction and the effects of micro-structural components. The distribution of the work roll temperature will affect the distribution of temperature in width direction.

The rest of this paper is organized as follows. In Section 2, a three-dimensional finite element based model of the strip temperature distribution is built. Many physical parameters of the strip are discussed. The strip density, thermal conductivity and specific heat capacity were analyzed. In Section 3, the simulation of a 3-D temperature distribution of the strip is finished. A conclusion is given in Section 4.

## 2. Finite Element Based Modeling of Temperature Distribution

In hot rolling process, temperature distribution of strip steel is complex, varied and many factors will impact on it. The strip is a rectangular solid and the factors that affect its internal and external temperature are not the same. As a result, a certain kind of the exact model or formula can not completely describe the changes of temperature on various locations within the strip. At present, finite element method is generally used to study and analyze the solid temperature field by the engineering field [10] and the temperature distribution of the object at some time and the temperature changes during some period afterwards can be obtained.

### 2.1. Principles of Thermal Analysis

Firstly, divide the object to be analyzed into several units (including the number of nodes). Secondly, solve the heat-balance equation on each node with certain boundary and initial conditions based on the principle of energy conservation. Thus the temperature of each node can be obtained. Based on that, other related quantities can be obtained.

PLANE55 unit is taken as an example which is shown in Figure 1. This unit is a quadrilateral with four nodes [11]. The temperature anywhere in the quadrilateral can be scattered to the four nodes, that is, the temperature field in the unit is described by  $T_i$ ,  $T_j$ ,  $T_k$  and  $T_m$ .

The area with a certain boundary is shown in Figure 2. It is divided into several PLANE55 units in ANSYS [12]. Every node in the area has a corresponding numeric symbol 1, 2, 3 and etc. Similarly, every unit has the symbol ①, ②, ③ and etc. These adjacent units are interconnected through common nodes.

In general, calculation accuracy is related with the units division. As a result, in order to achieve satisfied calculation accuracy, appropriate unit sizes must be deliberated according to the actual situation.

$$T = f(T_i, T_k, T_j, T_m) \quad (1)$$

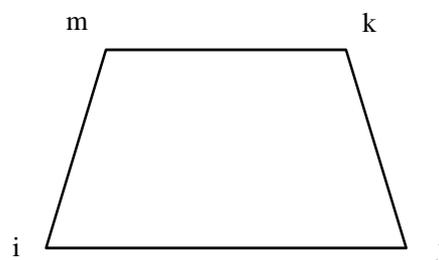


Figure 1. PLANE55 Unit

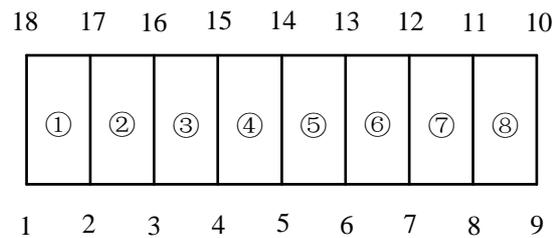


Figure 2. Division of an Area with a Certain Boundary

## 2.2. Heat Transfer Model

There are three kinds of finite element heat transfer mode, heat conduction, convection and radiation.

### 2.2.1. Model for Heat Conduction

Heat conduction can be defined as internal energy exchange caused by the temperature gradient between different parts of an object or two objects which are completely adherent [13]. Fourier's law is satisfied in heat conduction,

$$Q = -kA \frac{\partial T}{\partial x} \quad (2)$$

where  $Q$  is the heat flow between the nodes ( $W/m^2$ ),  $k$  is thermal conductivity ( $W/(m \cdot K)$ ),  $A$  is the heat transfer area between the nodes, minus means the heat flow direction to the lower temperature,  $T$  is the temperature ( $K$ ),  $x$  is the coordinates in the heat conduction surface.

### 2.2.2. Heat Convection to Spray

Heat lost through convection to the cooling sprays is applied to the surface nodes of the piece. Convection cooling losses are modeled using Newton's convection equation. Assuming that no energy is stored in the boundary layer, the heat lost from the piece is all transferred to the coolant. So,

$$Q_p = -Q_w = -h_w A_w (T_{surf} - T_w) \quad (3)$$

where,  $Q_p$  is the Heat flow of the plate,  $Q_w$  is the Heat flow of the water,  $h_w$  is the heat transfer coefficient of the coolant,  $A_w$  is the area of piece in contact with the coolant,  $T_w$  is the temperature of the coolant, and  $T_{surf}$  is the surface temperature of the piece.

### 2.2.3. Heat Convection to Air

At high temperatures typically experienced in rolling, radiation effect dominates over convection effects. However at lower temperatures, particularly those associated with cooling bed residence time calculations, convection becomes relatively important and cannot be neglected. Convective heat flow is calculated as follows,

$$Q = hA(T_s - T_\infty) \quad (4)$$

where  $T_\infty$  is the ambient temperature of the surroundings,  $h$  is the convective heat transfer coefficient.

This term dominates for high temperature. The convection model assumes that the thickness of the plate is much less than the width and therefore ignores the effects of convection from the sides.

### 2.2.4. Heat Radiation

Heat losses due to radiation to the surroundings are applied to the top and bottom surface nodes of the piece. Radiation heat losses from the piece and to the surroundings are calculated using the Stefan-Boltzmann equation,

$$Q_{piece} = \varepsilon_{piece} A_{piece} \sigma (T_{surround}^4 - T_{surf}^4) \quad (5)$$

where,  $\varepsilon_{piece}$  is the emissivity of the piece,  $T_{surround}$  is the ambient temperature of the surroundings, and  $T_{surf}$  is the surface temperature of the piece,  $A_{piece}$  is the surface area of the piece,  $\sigma$  is the Stefan-Boltzmann constant.

### 2.3. Energy Balance

Because the piece has been broken into a number of nodes to model internal conduction, an energy balance must be done on each node. The sum of all heat flows into the piece equals the rate of change of internal energy.

$$\sum Q_i = \frac{d}{dt} U_i \quad (6)$$

where,  $Q_i$  is the heat flow into the node  $i$ ,  $U_i$  is internal energy of the node  $i$ .

All nodes experience heat flows due to conduction to adjacent nodes. For surface nodes, additional heat flows are due to radiation, convection to sprays, and conduction to stand rolls.

If density and specific heat are assumed to be uniform and changes in internal energy are assumed to be proportional to changes in node temperature, internal energy can be expressed in terms of density, specific heat and node volume. This yields

$$\sum Q_i = \rho C_p V_i \frac{d}{dt} T_i \quad (7)$$

where,  $\rho$  is density,  $C_p$  is specific heat,  $V_i$  is the volume of node  $i$ ,  $T_i$  is temperature at node  $i$ . In integral form this becomes

$$\int_0^{\Delta t_{total}} \sum Q_i dt = \int_{T_{i_{initial}}}^{T_{i_{final}}} \rho C_p V_i dT_i \quad (8)$$

where,  $T_{i_{initial}}$  is the initial temperature at node  $i$ ,  $T_{i_{final}}$  is the final temperature at node  $i$ .

This equation can be integrated numerically to yield a finite difference equation for calculating the change in node temperature for a small time step.

$$\Delta T_i = \frac{\sum Q_i}{\rho C_p V_i} \Delta t \quad (9)$$

### 2.4. Determination of the Thermal Parameters

In the calculation of the temperature distribution, the physical parameter values of the strip must be known including the strip density, thermal conductivity and specific heat capacity, and these parameters related to temperature.

$$\bar{\xi} = \xi_\gamma V_\gamma + \xi_\alpha V_\alpha + \xi_p V_p \quad (10)$$

where,  $\bar{\xi}$  indicates the corresponding physical quantities,  $v$  is each phase proportion.

The relation between the thermal conductivity of the phase structure and temperature is as below,

$$\begin{aligned}
 \lambda_{\gamma} &= 17.168 + 0.01039T \\
 \lambda_{\alpha} &= 64.07 - 0.0432T \\
 \lambda_p &= 50.742 - 3.0567 \times 10^{-2}T + 1.1539 \times 10^{-7}T^2
 \end{aligned}
 \tag{11}$$

Equation 11 shows the relationship of each phase of tissue density changes with temperature.

$$\begin{aligned}
 \rho_{\gamma} &= 8111.44 - 0.5605T \\
 \rho_{\alpha} &= 7870.0 - 0.1644T - 5.7228 \times 10^{-4}T^2 + 4.5899 \times 10^{-7}T^3 \\
 \rho_p &= 7864.9608 - 0.34608T
 \end{aligned}
 \tag{12}$$

$\Delta H$  is the latent heat formula for austenite to ferrite and pearlite transformation,

$$\begin{aligned}
 \Delta H_{\gamma \rightarrow \alpha} &= 20789 - 15.632T - 0.24T^2 \\
 \Delta H_{\gamma \rightarrow p} &= 120848 + 52.42T - 0.158T^2
 \end{aligned}
 \tag{13}$$

Ferrite, pearlite and austenite specific heat capacity, respectively,

$$\begin{aligned}
 c_p^{\alpha} &= 14822.82 - 495.64T + 0.55237T^2 - 2.0495 \times 10^{-4}T^3 \\
 c_p^p &= -1158.44 + 11.31T - 0.024T^2 + 1.777 \times 10^{-5}T^3 \\
 c_p^{\gamma} &= 474.622 + 1.148T
 \end{aligned}
 \tag{14}$$

## 2.5. Finite Element Model of Strip

For example, three-dimensional strip plate model between stand 1 and stand 2 whose size is 1000×1200×14.29 (mm) is established. Three-dimensional thermal analysis unit is chosen during automatically division with a smart method. There are 13875 nodes and 6890 units in the finite element model. The division result is reasonable for our finite element model and accurate results can be calculated within the desired time.

## 3. Calculation and Analysis of Temperature Distribution for Rolling Strip

Considering the cooling process of strip steel, the temperature of the strip through the rough rolling export thermometer is uniform. However, the head and the tail of the strip are not cooled simultaneously when it goes through the descaling, finish rolling, and till left stages. As a result, a larger instantaneous temperature difference between the head and the tail is produced. Air-cooled district is long enough before the strip reach the finishing area that temperature difference between surface and center of strip is little after this period of cooling the, so the initial temperature can be regarded as uniformly distributed.

In order to accurately calculate the temperature distribution of the strip in finishing mill, a dynamic heat flux boundary condition must be imposed. Due to the relative motion of the strip and the cooling zone is determined, according to the principle of relative motion, we assume that the strip is still and finishing mill moves at the same speed along the opposite direction of strip movement.

### 3.1. Temperature Distribution of Strip in the Thickness Direction

According to previous analysis, because of the periodical boundary conditions during the strip passing through each pass in the finishing area, every stand is divided into three stages to analyze. Here we consider the period from the strip enter into the upstream stand till into the downstream stand.

The strip firstly enters the rolling deformation stage, which includes three forms of heat conduction, heat transfer, deformation and friction. According to the boundary conditions of temperature field established in previous section, Figure 3 shows the contours of the temperature field of the strip after going through rolling deformation zone. During rolling, heat transfer between rolled piece and outside is not significant, and heat conduction occurs when rolled piece contact with roller which leads to reduced temperature of the rolled piece. It can be seen from Figure 4, short rolling area, short contact period between the rolled piece and roller,

and big contact thermal conductivity will lead to the temperature dropped significantly on strip surface, while the strip center temperature is almost unchanged, which means there is a big temperature difference in the thickness direction of the strip.

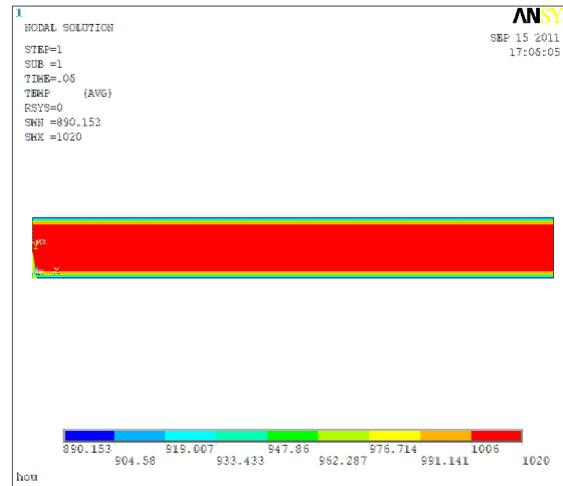


Figure 3. Temperature Distribution of Strip in Thickness Direction after Contact Area

After leaving the contact area, the strip enters the air-cooled areas and water-cooled area, the strip with water and air between the thermal conductivity is much smaller than the contact thermal conductivity, rolling exist within the phenomenon of thermal conductivity, high temperature center will provide low-temperature surface heat transfer, and the strip surface temperature will rise slightly, gradually decreases the temperature difference between inside and outside the strip.

The strip enters into the air-cooling stage, after rolling in the rolling temperature as the initial temperature of air-cooled stage. Existence of natural convection and radiation heat transfer in air-cooled stage and the environment, the ambient temperature of strip in the air-cooled stage with the relatively slow cooling rate, the strip plate temperature distribution is more uniform than the contact area.

The temperature distribution of strip before F2 and F7 stands are more uniform than in the contact area, as shown in Figure 4, 5, 6 and 7.

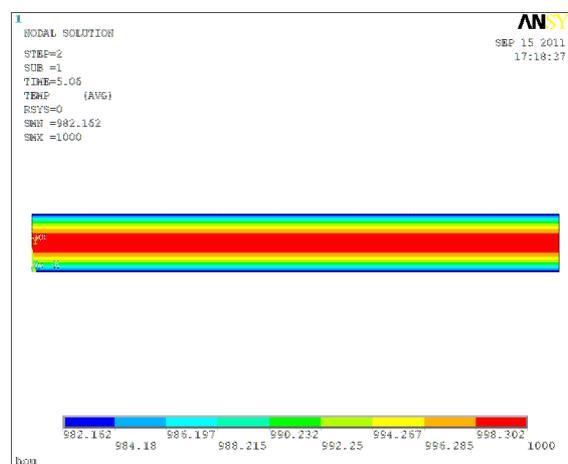


Figure 4. Distribution of Temperature before F2 Stand

142	982.16
143	986.69
144	991.00
145	994.48
146	997.10
147	998.91
148	999.97
149	1000.3
150	999.97
151	998.91
152	997.10
153	994.48
154	991.00
155	986.69
156	982.16

\*\*\*\*\* POST1 NODAL DEGREE OF FREEDOM LISTING \*\*\*\*\*

LOAD STEP= 0 SUBSTEP= 1  
 TIME= 5.0600 LOAD CASE= 0

NODE	TEMP
------	------

Figure 5. Temperature Value of Each Node after F1 Stand

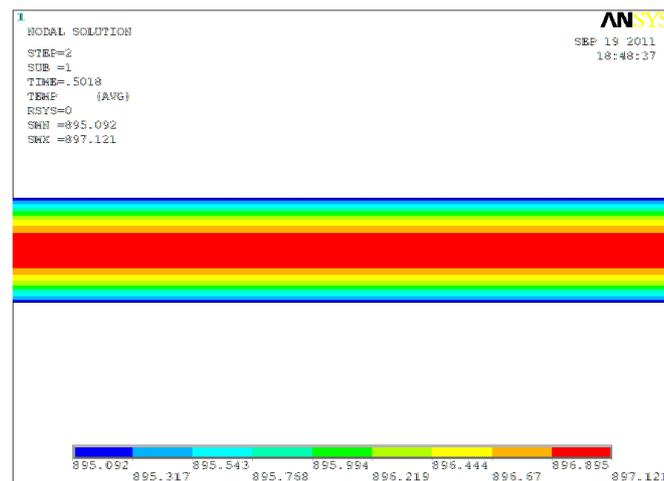


Figure 6. Distribution of Temperature before F7 Stand

It can be seen through the data analysis for seven stands, along with the conduct of rolling, the strip thickness is getting smaller and smaller, the difference of the surface and the internal temperature of the strip decreases, the temperature distribution are more uniform.

### 3.2. Strip Temperature Distribution in the Width Direction

Consider the distribution of the temperature of the roll width direction, in order to comprehensively analyze the temperature distribution of the roller. Parameters of mill as follows, work roll is 800 mm, the length of work rolls is 1580 mm, the width of rolling piece is 1200 mm, rotation linear velocity of roller is 1.02 mps, enter speed of the rolled piece is 0.92 mps. Figure 8 shows the temperature distribution in the roll cross-section of F2 stand.

```

***** POST1 NODAL DEGREE OF FREEDOM LISTING *****
LOAD STEP=      2  SUBSTEP=      1
TIME=    0.50180    LOAD CASE=    0

  NODE      TEMP
12013    895.09
12014    895.69
12015    896.21
12016    896.61
12017    896.90
12018    897.06
12019    897.12
12020    897.06
12021    896.90
12022    896.61
12023    896.21
12024    895.69
12025    895.69
12026    896.21
12027    896.61
12028    896.90
12029    897.06
12030    897.12

```

Figure 7. Temperature Value of Each Node after F7 Stand

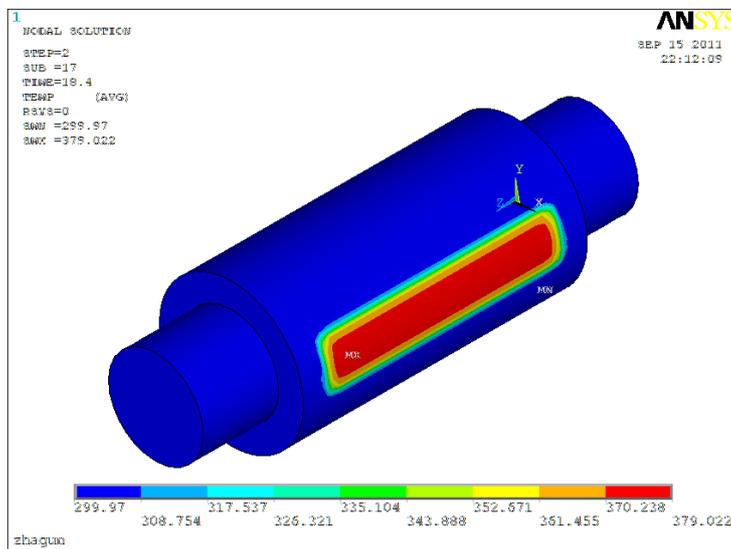


Figure 8. Temperature Distribution of the Roll Contact Area

Finite Element Analysis of the roll temperature distribution can be seen from above, and roll in contact with just the edge of the uneven temperature distribution, temperature around 70. Such uneven temperature distribution will result in uneven distribution of rolling temperature in contact with the rolling.

Consider the strip after the first rack rolling and the first rack and air-cooled District prior to the second rack and water-cooled after the strip cross-section as the analysis object. Figure 9 and 10 shows the strip temperature distribution in width direction before F2 and F7 stand.

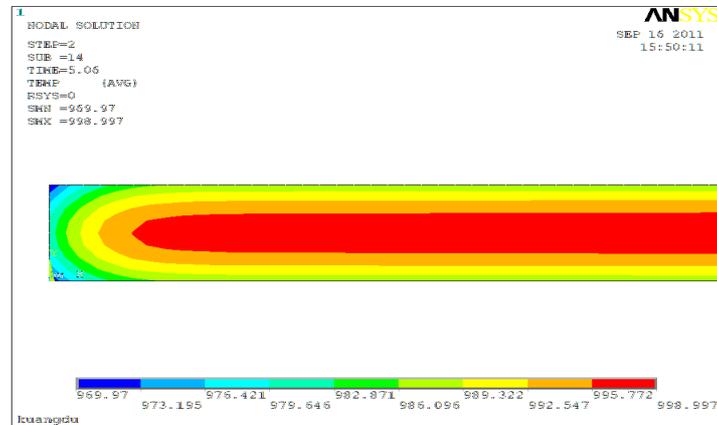


Figure 9. Temperature Distribution in Width Direction before F2 Stand

Can be seen from Figure 8, in the direction of the strip width is close to both sides of the local temperature distribution was uneven, Width direction of the larger temperature difference between center and edge temperature difference of about  $30^{\circ}\text{C}$ . This temperature distribution is likely to lead strip is not flat, affect its flatness. Therefore, it is necessary in the laminar cooling process in the subsequent cooling process along the strip width direction in order to ensure that the curl before the wide temperature distribution is relatively uniform, in order to obtain homogeneous, good flatness of the product.

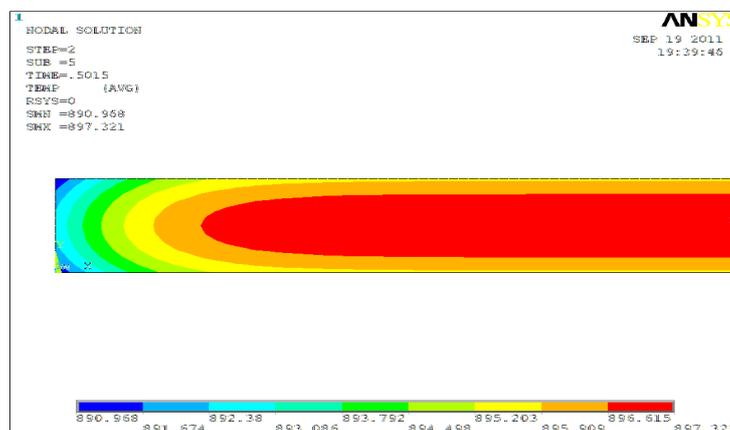


Figure 10. Temperature Distribution in Width Direction before F7 Stand

Figure 9 and 10 can be seen getting smaller and smaller in the rolled strip thickness is getting smaller and smaller, so the thickness of the strip on both sides caused by temperature drop, so the strip on both sides of temperature and center temperature difference smaller.

### 3.3. Strip Temperature Distribution in the Length Direction

Strip movement certainly has at different times into the cooling zone, which resulted in the strip cooling at different times in the length direction, so the strip temperature is different. In

order to comprehensively analyze the strip temperature distribution, the temperature distribution in the length direction of strip has to be considered. Consider the section of strip before the strip after completion of the first rack rolling to the second rack as the analysis object.

It can be verified by Figure 11. The temperature of the head and the tail are different. The head goes through longer period of cooling, so the temperature is lower than that of the tail.

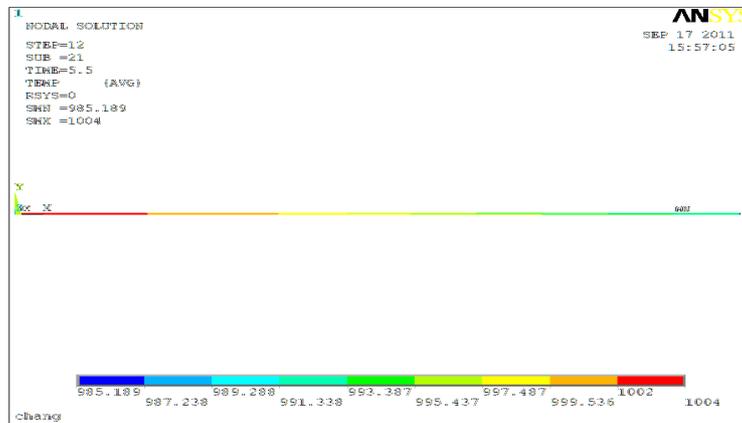


Figure 11. Temperature Distribution in the Length Direction between F1 and F2

### 3.4. Strip Three-Dimensional Temperature Distribution

Using the results of the previous analysis, we make a finite element analysis of three-dimensional distribution of the strip temperature. Figure 12 shows the strip temperature contours after the F1 stand.

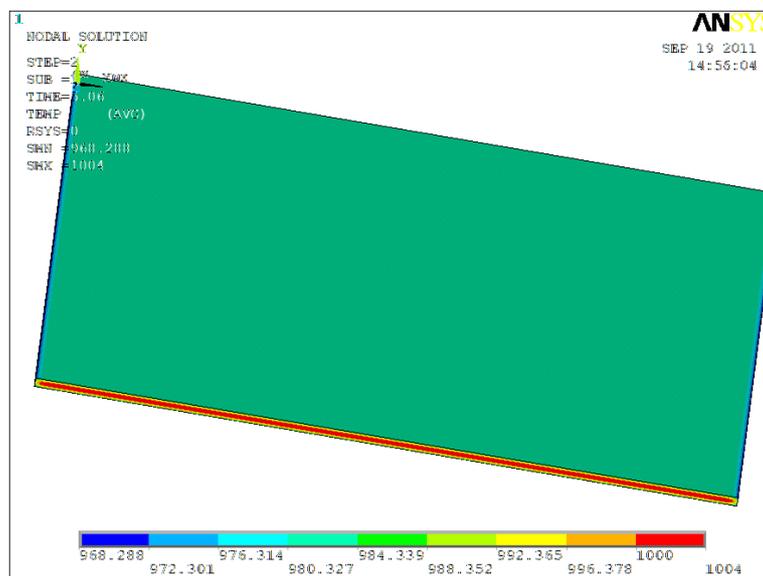


Figure 12. Strip Temperature Contours after F1 Stand

The seven stands calculation experiments were completed. The results show that the difference between the measurement and the simulation is 5°C. These show that as long as reasonable choose initial and boundary conditions, numerical calculation based on the finite

element model of the strip temperature is reliability, and this approach can be used as effective method of finishing temperature control.

#### 4. Conclusions

Three-dimensional distribution of strip temperature filed in hot rolling has been investigated. The results would provide effective guidance for Finishing Temperature Control (FTC), Automatic Gauge Control (AGC) and Automatic Shape Control (ASC). Simultaneously, the concept described above provides an excellent basis for comprehensive microstructure rolling and cooling control so that material properties can be kept constant over the entire strip length. We are sure that this new comprehensive control brings us a huge step forward in the control of material properties over the entire hot rolling process.

#### Acknowledgements

This work was supported by the NSFC under Grants (61074085), PR China. Also thanks the Beijing Key Discipline Development Program (no. XK100080537).

#### References

- [1] SA Balogun, GI Lawal OI Sekunowo and SO Adeosun. Influence of Finishing Temperature on the Mechanical Properties of Conventional Hot Rolled Steel Bar. *Journal of Engineering and Technology Research*. 2011; 3(11): 307-313.
- [2] Minghai Li, Haiting Yin. Improved Structure and Three-dimensional Numerical Analysis of Diesel Nozzle. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2012; 10(6): 1364-1369.
- [3] Hollander F. A Model to Calculate the Complete Temperature Distribution in Steel during Hot Rolling". *Iron Steel Inst*. 1970; 208: 46-74.
- [4] Devadas C and Samarasekara IV. Heat Transfer during Hot Rolling of Steel Strip, Ironmak. *Steelmak*. 1986; 13: 311-321.
- [5] Sluzalec Jr A. A Preliminary Analysis of Temperature within Roll Forging Dies, Using a Finite Element Method, *Int. J. Mach. Tool Des. Res.* 1984; 24: 171-176.
- [6] Guangguo Zhang, Jing Sheng, Feng Wang. A Finite Element Analysis of the Rectangle Spline Broach. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2012; 10(8): 2125-2130.
- [7] Teseng AA, Lin FH, Gunderia AS and Ni DS. Roll Cooling and Its Relationship to Roll Life. *Metallurgical and Materials Trans. A*. 1990; 20: 2305-2320.
- [8] BK Chen, PF Thomson, SK Choi. Temperature Distribution in the Roll-gap during Hot Flat Rolling". *Journal of Materials Processing Technology*. 1992; 30(2): 115-130.
- [9] MEI Rui-bin, LI Chang-sheng. Analysis of Strip Temperature in Hot Rolling Process by Finite Element Method. *Journal of Iron and Steel Research, International*. 2010; 17(2): 17-23.
- [10] Di Tang. China's Hot Strip Mill Production and Technological Progress for 20 Years. *Rolling*. 2004; 21(6): 1-10.
- [11] VB Ginzberg. With High Accuracy the Theory and Practice of Strip Rolling. *Metallurgical Industry Press*. 2000: 231-234.
- [12] Steven C Chapra, Raymond P Canale. *Numerical Methods for Engineers*. McGraw Hill Companies, Inc. 2000: 832-844.
- [13] Xiumei Wang, Guodong Wang, Xianghua Liu. Neural Network Rorce Prediction in Hot Strip Mill Rolling. *Iron and Steel Research*. 1998; 10(4): 72-79.