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Significance of Heat Conduction Parameter along the Rolling Direction in the Thermal Modeling of the Hot Rolling Process

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Abstract
Obtaining temperature distribution data of slabs under rolling is essential as the mechanical and metallurgical properties of the metal under this process vary with temperature. Using the control volume method, a mathematical model is employed in this study to predict slab temperature in the hot roll process at Mobarakeh Steel Company. The effects of different parameters including the heat resulting from plastic deformation and slab material are investigated. Additionally, heat conduction along the rolling direction in the slab, ignored in most previous studies, is included in our investigation. The study indicates the importance of this term in the accuracy of the results obtained.

Keywords: Rolling, Heat transfer, Slab.

Symbols

q	Heat generated due to plastic deformation (J/m^3)
$\dot{q}$	Energy source term (W/m^3)
c_p	Specific heat capacity $(J/Kg.K)$
ρ	Density (kg/m^3)
k	Coefficient of thermal conductivity $(W/m.K)$
T	Slab temperature *(K)*
$\frac{D}{Dt}$	Material derivative
d_1	Initial thickness *(m)*
d_2	Final thickness *(m)*
N	Angular velocity of the roll (rad/s)
h_c	Heat transfer coefficient between slab and roll $(W/m^2.K)$
σ_y	yielding stress (N/m^2)
ΔT_{def}	Temperature rise due to plastic deformation *(K)*
T_∞	ambient temperature *(K)*
h_∞	Convection heat transfer coefficient $(W/m^2.K)$
σ	Stephan Boultzman constant $(W/m^2.K^4)$
ε	Emissivity coefficient
T_{rol}	Roll temperature *(K)*
s_c	temperature independent term of the source term (W/m^3)
s_p	coefficient of temperature of the source term W/m^3K

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Introduction

Hot rolling is a method used in the production of thin metal slabs. According to this method, upon leaving the furnace, the slab passes under a water spray of 180 bars for the oxide scaling formed on it to be removed. Then, it is subjected to several roll passes whereby the desired thickness is obtained. Hot rolling involves two stages of roughing and finishing. In the former, the slab receives three reciprocating roll passes in each shelf to loose thickness by 18%, 25%, and 30%. The hot rolling line at MSC involves two roughing stages after which the slab enters the finishing stage. In this stage, the slab passes under 7 rolls to get to its final thickness. Researchers working in the field of hot rolling have classified the heat transfer mechanisms in the process as follows (Figure 1):

1. Temperature drop due to radiative heat transfer between the slab and the surrounding environment;
2. Temperature drop due to heat convection between the slab and air;
3. Temperature drop due to water spray at a (the) pressure of 180 *atm.* at the descaling unit;
4. Temperature drop due to heat conduction between the slab and the rolls in the deformation unit; and

1. Associate Professor
2. Ph.D Student

5. Temperature rise in the hot roll mill due to plastic deformation.

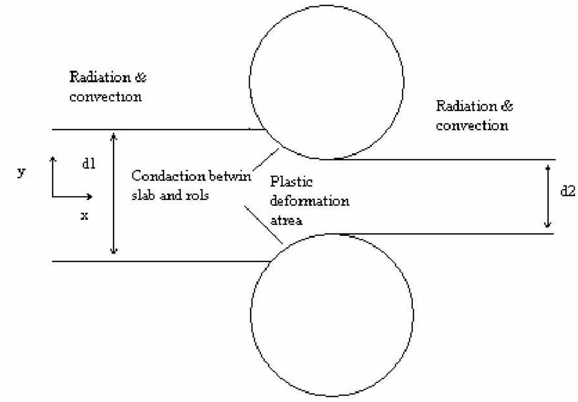

Fig. 1. Heat transfer mechanism in the hot roll process.

The hot roll process has recently been the subject of researches carried out by many workers in the field. Empirical relations have been used in some studies in an attempt to reduce the computation cost. For instance, Devadas and Samarasekera obtained the temperature distributions in strips and rolls using empirical relations and the finite difference method [1]. Most researchers ignored heat conduction along the rolling direction. Chen, Samarasekera, Kumar, and Hawbolt, ignoring heat conduction along the rolling direction and the direction orthogonal to the plate, investigated the mill scale effects on slab temperature distribution [2]. Using the pseudo-bond graph method and ignoring heat conduction along the rolling direction, Pal and Linkens determined slab temperature distribution [3]. Temperature distribution has also been computed by Brawn and Rohloff through semi-analytical finite element method assuming physical properties of the material to be independent from temperature and strain distribution at the deformation area to be homogenous [4]. Lausraous and Jonas have also used finite difference method to obtain temperature distribution, and the results are used to predict the final structure of the metal [5]. A number of experimental studies have also been carried out to obtain heat transfer coefficients at the strip-roll contact area for different lubricants [6-8]. Jeswiet and Zou performed a number of experiments to compute temperatures, heat flux, and conductive heat transfer coefficient during rolling [9].

Complex heat convection occurs on slab surface in contact with air. In recent decades numerous studies have been carried out on complex heat convection [10, 11].

Theorical formulation

In this paper, a mathematical model of heat transfer using the finite volume method is utilized to compute the temperature distribution of the slabs in hot rolling process. The model is based on empirical relations to determine heat conduction coefficients, emissivity correlations in radiative heat transfer, and the relationship between temperature and physical property changes in the metal. The assumption here is that the slab with a given temperature enters the roughing stage and leaves it after the process is complete. The objective is to compute the final temperature of the slab after it passes through the first roughing mill.

According to the Lagrangian coordinate, the energy equation in the Cartesian system for the general conditions is as follows:

$$\frac{\partial}{\partial x}(k\frac{\partial T}{\partial x})+\frac{\partial}{\partial y}(k\frac{\partial T}{\partial y})+\frac{\partial}{\partial z}(k\frac{\partial T}{\partial z})+\dot{q}=\rho c_p\frac{DT}{Dt} \qquad (1)$$

Where, $\dot{q}$ is the energy source term and $\frac{DT}{Dt}$ is the material derivative. The energy equation can be simplified on the basis of the following assumptions:

1. Heat transfer in the direction Z (orthogonal to the plane of Figure 1) is ignored, as the slab width is far greater than its thickness.

$$\frac{\partial T}{\partial z}=0 \qquad (2)$$

2. Heat conduction in the direction of strip motion due to its high speed is ignored [2,3]; in other words:

$$\frac{\partial}{\partial x}(k\frac{\partial T}{\partial x})=0 \qquad (3)$$

Since temperature has a sharp drop at a small distance from the area under rolling, the above assumption seems to be incorrect. In the present paper, we have dealt with the problem under both conditions and compared the results. Once the above simplifications are made in the equation, and when the conductive heat in the rolling direction is ignored, the energy equation takes the following form:

$$\frac{\partial}{\partial y}(k\frac{\partial T}{\partial y})+\dot{q}=\rho c_p(\frac{DT}{Dt}) \qquad (4)$$

And in case, the above parameter is not ignored, Eq. (5) obtains:

$$\frac{\partial}{\partial x}(k\frac{\partial T}{\partial x})+\frac{\partial}{\partial y}(k\frac{\partial T}{\partial y})+\dot{q}=\rho c_p(\frac{DT}{Dt}) \qquad (5)$$

As mentioned above, $\dot{q}$ in the above equation is the energy source term. During the hot rolling process, heat is generated at the slab-roll contact area as a result of plastic deformation, which must be included in the term $\dot{q}$.

The heat generated due to plastic deformation in the deformation zone is computed from equation (6) [12]:

$$q=\sigma_y\ln(\frac{d_1}{d_2}) \qquad (6)$$

Where, σ_y is the yielding stress of the metal; d_1, the initial thickness; and d_2 is the final thickness of the slab. Given the above equation, increase of the temperature per unit of volume in the slab due to plastic deformation is as follows:

$$q=\rho c_p\Delta T_{def}=\sigma_y\ \ln(\frac{d_1}{d_2}) \qquad (7)$$

$$\Delta T_{def} = \frac{\sigma_y}{\rho c_p} \ln(\frac{d_1}{d_2}) \qquad (8)$$

Therefore $\dot{q} = \frac{dq}{dt}$ is used as the energy source term.

Boundary and initial conditions

The initial condition effected in each time step is the same as the temperature of the element in the preceding step. Therefore, the initial condition in the first time step is the furnace temperature.

Since the geometry is assumed to be symmetrical, half of the whole shape is taken into account and the symmetrical line is assumed to be the insulating line. In the zones before and after the rolling point, where the slab is in contact with air, we have both convective and radiative heat transfer. The boundary conditions, therefore, are:

$$-k\frac{\partial T}{\partial y} = h_\infty (T - T_\infty) + \varepsilon\sigma(T^4 - T_\infty^4) \qquad (9)$$

Where, T_∞ is the ambient temperature, ε=0.8 [12] is the emissivity coefficient and h_∞ is the convective heat transfer coefficient between the surface and the surrounding air.

The slab and the roll are in full contact with heat transfer taking place between them. This heat transfer can be modeled by [6]:

$$-k\frac{\partial T}{\partial y} = h_c (T - T_{rol}) \qquad (10)$$

Where, h_c is the heat transfer coefficient obtained from Table 1 and T_{rol} is the roll temperature which is taken to be constant at 60 °C.

Table 1. Heat transfer coefficients in contact zone $h_c(kW/m^2K)$ [7].

with oxide scale	Without oxide scale	Conditions for the use of lubricants at contact area
7-10.6	29.1-34.9	Without lubricant
10.6	23.3-81.4	water
5.8	200-460	Hot oil
12.8-23.3	68.8-175	Hot oil+20% $CaCo_3$
-	12.79-17.4	Hot oil+40% $CaCo_3$
-	5.8	KPO_3

If the conductive heat transfer in the rolling direction is not ignored, then two sets of boundary conditions on the two sides of the slab are required. As both radiative and convective heat transfer occur on the two sides, then the boundary conditions are as in Equation (11).

$$-k\frac{\partial T}{\partial x} = h_\infty (T - T_\infty) + \varepsilon\sigma(T^4 - T_\infty^4) \qquad (11)$$

Solution method

We used the control volume method in the numerical solution of the conduction problem. For our purposes, we have adopted the implicit method in the solution of the problem as it requires no convergence conditions and it satisfies our purposes in terms of simplicity and physical behavior. In the one-dimensional case (y and t), the discretized heat transfer equation takes the following form [13]:

$$\begin{aligned} & a_P T_P = a_N T_N + a_s T_s + b \\ & a_N = \frac{k_n}{\delta y_n} \\ & a_s = \frac{k_s}{\delta y_s} \\ & a_P^0 = \frac{\rho c_p \Delta y}{\Delta t} \\ & b = s_c \Delta y + a_P^0 T_P^0 \\ & a_P = a_N + a_S + a_P^0 - s_P \Delta y \end{aligned} \qquad (12)$$

We can linearize the $\dot{q}$ as a function of temperature

$$\dot{q} = s_c + s_p T_p \qquad (13)$$

Where s_c and s_p are the temperature independent term and the coefficient of temperature, respectively. In this work, $\dot{q}$ is not a function of temperature, therefore $s_p = 0$ and $s_c = \dot{q} = \sigma_y \ln(\frac{d_1}{d_2})$.

The grid is designed in such a manner that the nearer we get to the surface, the smaller the size of the elements is, (Figure 2) because temperature variations are sharper at points near the slab surface. In the one dimensional solution, 40 elements in the y direction and 20 time steps in the contact region were considered.

As we are taking up a Lagrangian coordinate, we have to select one point on the slab and trace its variations through time. The diagram for this process in the one-dimensional system is shown in Figure 2.

In the two-dimensional system (t, y, x), the discretized equations are of the form in equation (14) [13]:

$$\begin{aligned} & a_P T_P = a_N T_N + a_s T_s + a_E T_E + a_W T_W + b \\ & a_N = \frac{k_n}{\delta y_n} \\ & a_s = \frac{k_s}{\delta y_s} \\ & a_E = \frac{k_e}{\delta x_e} \\ & a_W = \frac{k_w}{\delta x_w} \\ & a_P^0 = \frac{\rho c_p \Delta x \Delta y}{\Delta t} \\ & b = s_c \Delta x \Delta y + a_P^0 T_P^0 \\ & a_P = a_N + a_S + a_E + a_W + a_P^0 - s_P \Delta x \Delta y \end{aligned} \qquad (14)$$

To model the slab movement in this situation, we may assume that the slab is fixed but the roll is passing on it. Therefore, the grid system at each time step is shown in Figures 3 to 5. The elimination of elements continues until the plotted curve is complete. One element is eliminated at each time step and the boundary conditions are transferred to the new boundary. In the two dimensional solution, 800 elements in the x direction and 40 elements in the y direction were considered. Therefore, the total number of control volumes is 32000. The point under consideration passes through rolling stands and the temperature is recorded at each time step.

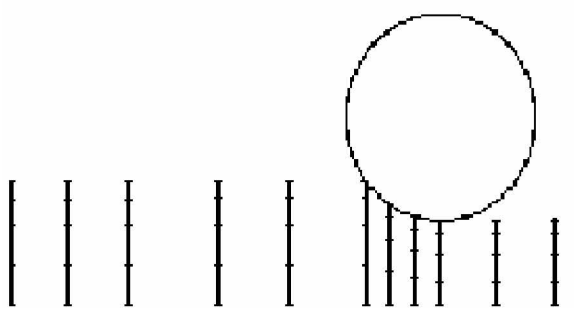

Fig. 2. One-dimensional grid in each time-step.

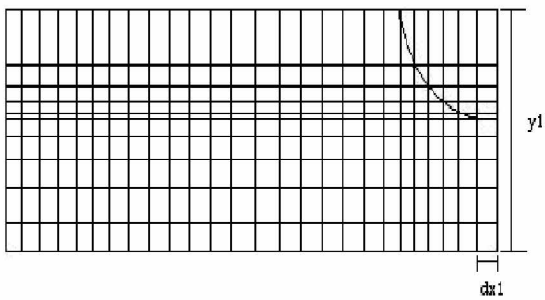

Fig. 3. Two-dimensional grid in the first time-step.

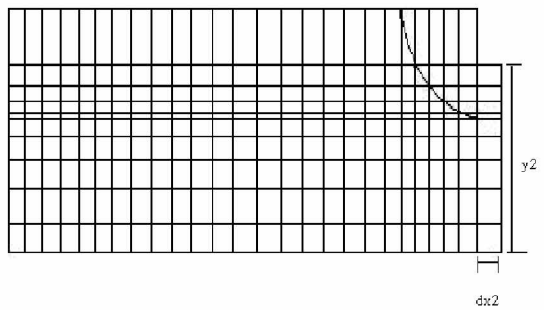

Fig. 4. Two-dimensional grid in the second time-step.

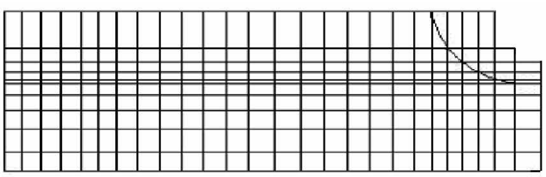

Fig. 5. Two-dimensional grid in the third time-step.

Results and Discussion

Our objective in this paper is to investigate the slab thermal behavior and the effects of certain parameters of the rolling process on temperature distribution along the slab. The two programs developed for this purpose using MATLAB are capable of modeling the parameters involved. The assumption in these programs is that at the moment of initiation, the slab head is in contact with the roll. Then, the slab continues its movement ahead until at the end of the rolling process, the slab end comes into contact with the roll (Figure 6). The programs receive the initial temperature of one element from the slab as input and work out (as output) the temperature at the end of the process.

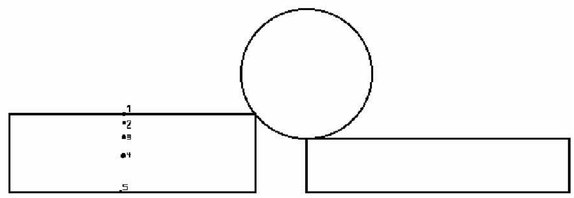

Fig. 6. Schematic view of the solution domain.

The first program ignores the conduction of heat along the rolling direction and uses equation (4) to solve the heat problem. Figure 2 shows the grid system used in the first program. The second program takes into account the parameter ignored in the first program and uses equation (5) to solve the heat equation. The grid system used is shown in Figure 3.

Typically, low-carbon steel slabs are selected for the rolling process for their satisfactory deformability. In continuation, different types of low-carbon steels and their temperature distributions at the contact area are compared. The values for k and c_p for several steels are presented in Table (2) [14]. In the present equations, temperature is given in degrees centigrade.

Table 2. Heat transfer coefficients for steels[14].

$c_p\,(J/kg^{\circ}C)$	$k\,(W/m^{\circ}C)$	Steel name
446+.4592 *T*	*61.32-.0336T*	AISI1005
446.78+.457T	*61.32-.034T*	AISI1006
446.33+.2287T	*52.58-.0253T*	AISI1021
459.2+.224T	*52.58-.0253T*	ST37
403.125+.625T	*65.2-.034T*	ST12

Figure 7 shows temperature curves for point 1 (Figure 6) at the contact area between the slab and the roll for the three different steels *AISI1005*, *AISI1006*, and *AISI1021*.

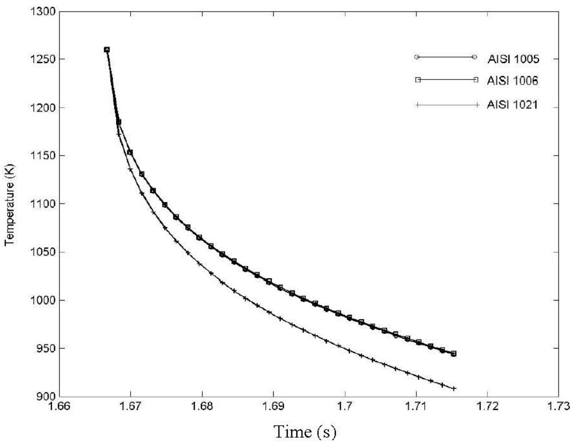

Fig. 7. Surface temperature curves in the deformation area.

The curves for the first two types of steel entirely overlap due to the very close similarity of their characteristics. The higher the value for k , the better the heat transfer from inner layers to the slab surface and, hence, the smaller the temperature drop occurring at the slab surface. This is especially observed in *AISI1021* which has a lower value of k . Another point observed in the curve is the sharp temperature drop on the slab surface during the initial moments of contact with the roll, which is gradually replaced by temperature drop resulting from heat transfer from internal layers to the surface.

In a similar manner, Figure 8 presents the curves for steels *ST37* and *ST12*.

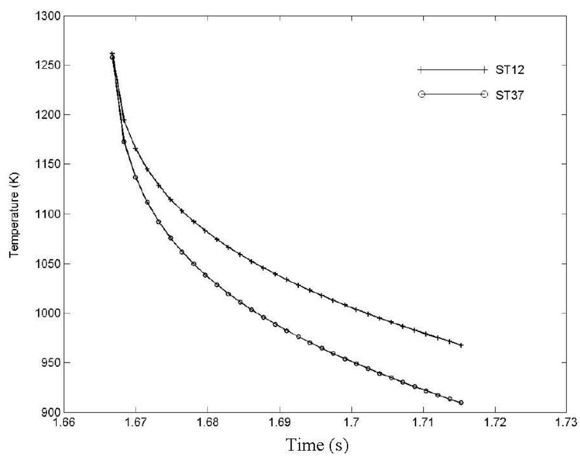

Fig. 8. Surface temperature curves in the deformation area.

Figure 9 shows the curve for the temperature variations of one point near the surface of the slab at the contact area for steels *ST37* and *ST12*.

Similarly, Figure 10 shows the curves for steels *AISI1005*, *AISI1006*, and *AISI1021*.

At points inside the slab, temperature variation is greatly affected by the amount of plastic deformation and by coefficient c_p obtained from equation 7. As the amount of heat generation due to plastic deformation is the same for these different situations, it follows that metals with a lower c_p exhibit greater temperature variations.

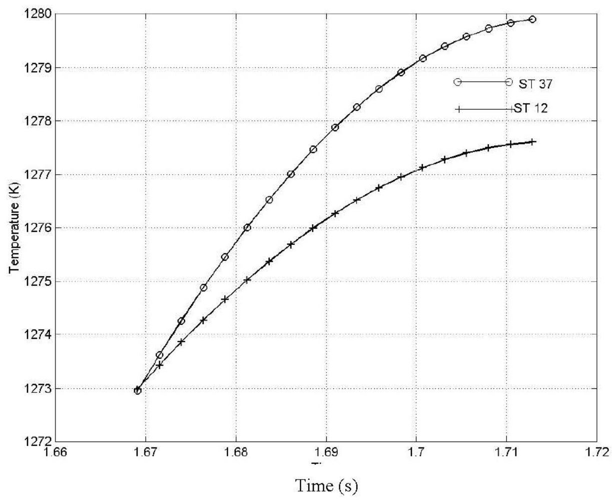

Fig. 9.Temperature variation of one slab internal point.

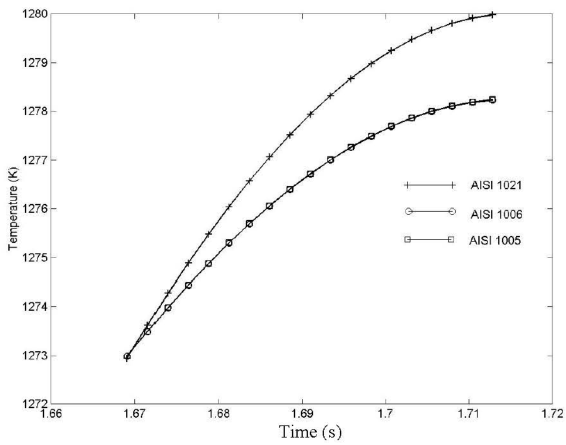

Fig. 10. Temperature variation of one slab internal point.

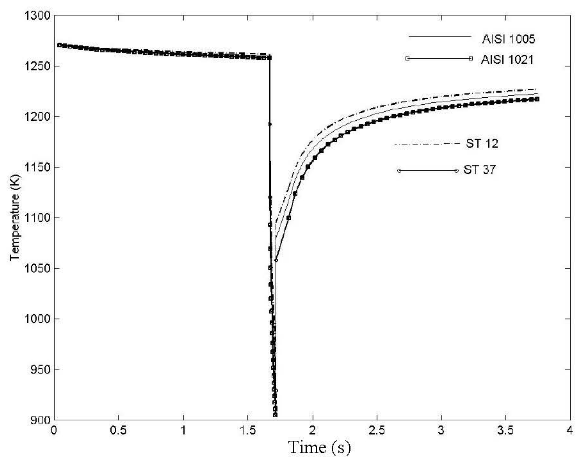

Fig. 11. Surface temperatures for various steels.

Figure 11 plots the curves for the temperature of point 1 in different steels. The important point here is that material has seemingly no role to play in determining surface temperatures.

It is evident from the above observations that coefficient c_p plays a significant role in the temperature of the slab internal points while coefficient k plays an important role in surface point temperatures.

As already mentioned, the roughing process has three reciprocations in each shelf as a result of which the slab thickness reduces by 18%, 25%, and 30% during the three passes to get to its ultimate thickness. Effecting these on points 1 through 4 and plotting the resulting temperature-time curves yields Figure 12. In areas where point 1 comes into contact with the roll, the temperature has a sharp drop but the cause for the sharp temperature drop is the heat transfer from inner layers to the surface after the point leaves contact with the roll. This causes the temperature of point 4 to exhibit a decrease after each roughing stage. As observed in Figure 12, temperature variation decreases as we move toward the slab center. It must be mentioned in passing that the stepwise increase in temperature at point 4 is due to plastic deformation.

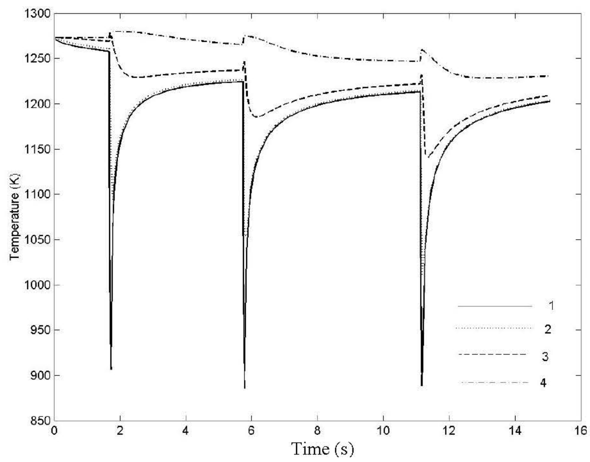

Fig. 12. Temperatures of points 1 through 4 during three roll passes.

It was mentioned earlier that most researchers have ignored conduction of heat transfer along the rolling direction in favor of heat transfer due to mass movement. However, the assumption may seem to be false as the area at a small distance from the roll loses temperature by about 350° C. Now let us consider the problem in a two-dimensional system (a function of t, x, and y). We consider a point along the slab, draw its temperature curve versus time for the one-dimensional (a function of t and y) and two-dimensional systems, and finally compare the results. The temperature curve for point 1 on the slab surface is shown in Figure 13 for the two-dimensional solution. For comparison, Figure 14 shows the same situation for the one-dimensional solution.

It is observed that minimum temperatures at the area below the roll are the same. The difference between these two solutions lies in the fact that temperature increase occurs more rapidly in the two-dimensional solution.

This state of affairs stems from the fact that in the one-dimensional solution, the surface element only receives heat from its underlying elements while in the two-dimensional solution, it additionally receives heat from adjacent elements and, as we already know, the temperature of near-surface elements is far higher than that of the surface element. In the two-dimensional solution, therefore, temperature rises more and faster. This phenomenon even causes surface temperature in the two-dimensional solution to increase after an elapse of time unlike the case in one-dimensional solution where the surface temperature constantly decreases at the contact area.

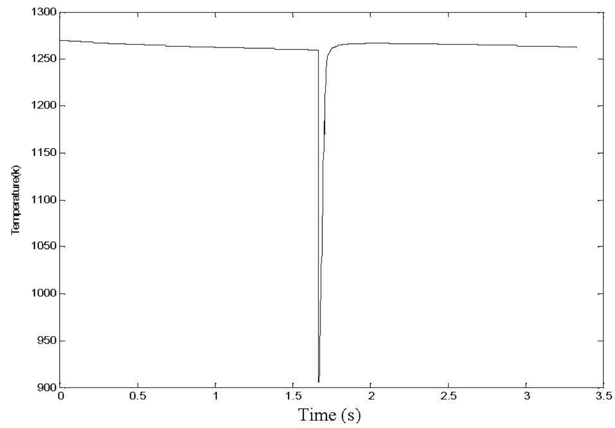

Fig. 13. Temperature of point 1 in the two-dimensional solution.

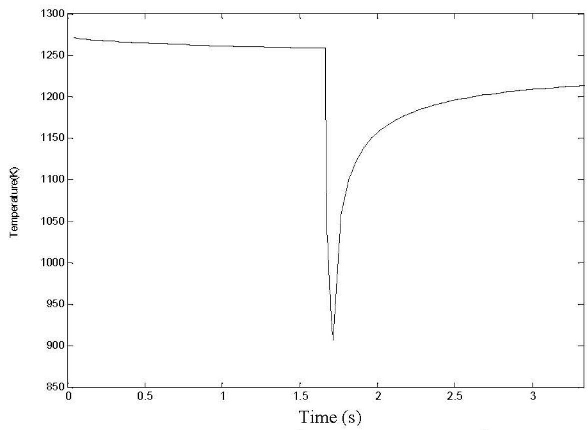

Fig. 14. Temperature of point 1 in the one-dimensional solution.

For validation of the results, the Serdinski's data were used in this program. He suggests that the temperature drop in the contact region follows this semi analytic equation [12]:

$$T - T_2 = \frac{60h_c\sqrt{\frac{d_1/d_2}{Rd_1}}(T - T_{rol})}{\pi\rho c N(1 - d_1/d_2)} \qquad (15)$$

Where in Eq. (15) h_c=27 $\frac{kJ}{m^2 s^\circ C}$, ρ=7570 $\frac{kg}{m^3}$, c= 650 $\frac{J}{kg^\circ C}$, N =44.1 $\frac{rad}{s}$, $\frac{d_1}{d_2}$ =0.3, $d_1 = .3m$, T_{rol}=200 $^\circ C$ and T_2=*1273K* and T are the initial and final temperature of the slab surface, respectively. From Eq. (15) T is *1269K.This data used in the program and T=1140K* was the result. The error is %10 and good agreement was seen between the results.

Conclusions

1- Coefficient c_p plays a significant role in the temperature of slab internal points while coefficient k plays its role in determining the temperature of surface points.
2- The most significant factors involved in determining the temperature of the center of the slab include the temperature of the rolling preheating furnace, slab material, and the amount of plastic deformation at the rolling area.
3- Conduction of heat transfer along the rolling direction has a significant effect on temperature variations at the area under the roll, and cannot be ignored.

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