

# Effect of Water-Cooled Skids on Steel Slab Temperature Homogeneity during Reheating Prior to Hot Working

H. Abuluwefa, and A. Alfantazi

**Abstract**— Reheating of steel prior to hot working is an important process through which the slabs are brought to thermal homogeneity enabling the rolled products to exhibit constant mechanical and thermal properties. In pusher-type steel reheat furnaces, slabs are pushed along the furnace riding on top of water-cooled steel skids, resulting in the occurrence of low temperature strips along the area of contact between the bottom surface of the slab and the skids surface. This work models the reheating process of the slabs where the temperature distribution in the riding slab is calculated in two dimensional heat transfer analysis and using actual reheating parameters obtained from an industrial pusher-type steel reheat furnace as an input to the model. Temperature images and profiles in the affected area of the slab by the cooling process are plots for different skid heights of 4, 2, 3 and 1 cm, representing skid wear out. Results showed a considerable effect of cooling the skids on the temperature distribution in the riding slab. Temperatures were lowered 300 to 500°C from the desired reheating temperature of about 1230°C in the areas of the skid-slab contact and up to depths of about 10 cm in the slab.

**Index Terms**— reheat furnaces, skid marks, steel reheating, temperature modeling.

## I. INTRODUCTION

The mechanical properties of metals are the most important factors, having a direct effect on metal quality, a goal all manufacturing companies strive to achieve. In steel making, there are many ways to improve steel quality, some of them are chemical and some are thermal operations. Chemical methods include the addition of alloying elements during the melting and casting process of molten steel, enabling the steel to attain the desirable mechanical and chemical properties. As for thermal treatments to improve the mechanical properties, the steel, in general, is heated to a specified temperature and kept at this temperature for a certain period of time, in order to give the metal time to reorganize its atoms in a more stable positions, and to get rid of internal stresses. In thermal treatments there is an important factor that should be met which is the thermal homogeneity of the metal being thermally treated. If temperature homogeneity is not attained thermal gradients will exist within the metal resulting in variations in the mechanical and chemical properties in the metal being processed.

One of the thermal operations in the steel industry is the reheating of steel slabs or billets prior to hot working. The

purpose of this operation is to heat the steel to a specified temperature of approximately 1230 °C for a period of time to allow the steel to homogenize in temperature and chemical composition prior to being rolled to flat products. During this reheating process and because the slabs are in contact with the water-cooled rails they ride on inside the furnace, skid marks develop which are characterized by their lower temperature compared to the rest of the steel slab. The occurrence of temperature gradients within the slab results in differences in the mechanical properties of the rolled products. This work models the slab heating process in order to see the extent of temperature variations within the slab due to heat withdrawal as a result of the direct contact between the slab surface and water -cooled skids as they wear out.

### A. Water- Cooled Skid System

The actual water-cooled skid system in the pusher-type steel reheat furnace consists of supporting pillars and insulated water pipes running along and across the inside of the furnace as shown in Fig. 1. Welded on top of these water-cooled pipes are steel rails of 4 cm<sup>2</sup> in cross section.

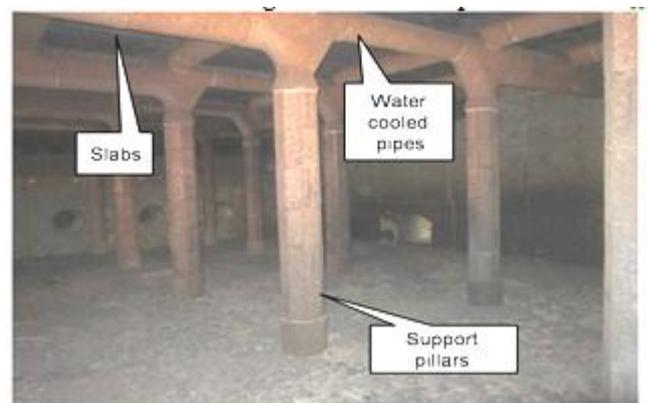


Fig. 1. Water-cooled pipes over which the slabs ride on during the reheating operation at the Libyan Iron and Steel Company (LISCO).

These rails are in direct contact with the bottom surface of the slabs as shown in the schematic in Fig. 2. Heat is withdrawn from the slab through the area of the slab-skid contact due to cooling creating areas and strips of low temperatures in the slab.

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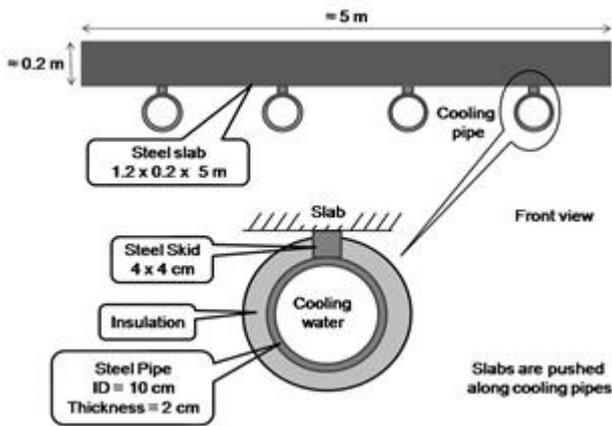


Fig. 2. Schematics of the slab-skid system under consideration.

II. MODELING METHODOLOGY

Since it is not possible to conduct direct measurements or carryout experimental work in the actual steel reheat furnace (due to the aggressive nature of the environment existing in these furnaces) this necessitates studying this problem mathematically. The temperature distribution in the slab as it moves along the furnace is calculated using a two dimensional heat transfer approach. The input of these calculations as well as slab dimensions are taken as the actual values used in the industrial steel reheating furnace. The slab cross section through its length is divided into equally-spaced temperature nodes separated by a 0.25 centimeter distance in the two directions, as shown in the schematics of Fig. 3.

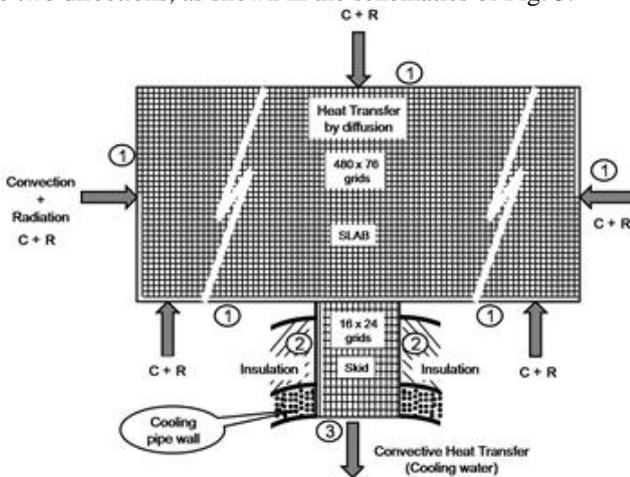


Fig. 3. Schematics showing the grid systems used to calculate temperature distribution in the slab and skid.

Temperatures at each node are calculated numerically by solving the governing heat equation using the finite difference scheme.

A. Assumptions

In calculating heat transfer through the steel slab during reheating, and to simplify the calculations, the following main assumptions were made:

- Thermal properties of the steel are kept constant, i.e., independent of temperature.
- No effects of scale forming on the steel surfaces.

B. Mathematical Analysis

There are many models in literature where steel reheating process is considered [1] - [6]. In this work, a simple approach is taken by considering a two dimensional transient heat transfer by conduction equation to model the temperature distribution in the slab and skid during reheating in the pusher reheat furnace. This equation is:

$$\frac{d^2T}{dx^2} + \frac{d^2T}{dy^2} = \frac{1}{\alpha} \frac{dT}{dt} \tag{1}$$

where the parameters  $T$ ,  $\alpha$  and  $t$  are temperature ( $^{\circ}\text{C}$ ), diffusivity ( $\text{m}^2/\text{s}$ ) and time (s), respectively. Coupled with appropriate boundary conditions evolved in the heating process, this equation can be solved giving temperature distributions in the calculation domain shown in Fig. 2. The method adopted in solving this equation is by the use of the finite difference technique and solving the resulting equation implicitly. Referring to the nodal distribution in the slab shown Fig. 2, (1) can be discretized in space and time resulting in the general equation [7], [8]:

$$(1 + 4F_o)T_{(n,m)}^{p+1} - F_o(T_{(n+1,n)}^{p+1} + T_{(n-1,m)}^{p+1} + T_{(n,m+1)}^{p+1} + T_{(n,m-1)}^{p+1}) = T_{(n,m)}^p \tag{2}$$

where  $F_o$ ,  $n$  and  $m$  are Fourier's number, vertical and horizontal directions, respectively. This equation is in the implicit form since current temperatures at time  $(p+1)$  at the different nodes are calculated simultaneously. This method of calculation is characterized by the fact that it is unconditionally stable and its accuracy increases by decreasing the time interval ( $\Delta t$ ) as well as the space interval ( $\Delta x$ ) chosen for the calculation domain. Equation (2) can be solved by applying the boundary conditions specific to the problem configuration shown in Fig. 2.

In this case we have three types of boundary conditions: convection between the in-furnace gas and slab surfaces (marked 1 in Fig. 2), adiabatic boundary condition between the skid sides and insulation materials (marked 2) and convective boundary condition between the skid bottom and the cooling water (marked 3). The surfaces exposed to the furnace atmosphere receive heat flux by gas convection and radiation, and hence, (2) becomes:

$$(1 + 4F_o)T_{(n,m)}^{p+1} - F_o(T_{(n+1,n)}^{p+1} + T_{(n-1,m)}^{p+1} + T_{(n,m+1)}^{p+1}) = T_{(n,m)}^p + F_o T_s^{p+1} \tag{3}$$

$T_s$  in the above equation is the slab surface temperature which is a function of heat transfer by gas convection and radiation. Sang Han. et al. [4] used the following equation to calculate slab surface temperature in a reheat furnace,  $T_s$ .

$$T_s = \frac{-k_g \frac{T_F}{\Delta x} \Big|_g + \varepsilon_w q_{in}^R + 3\varepsilon_s \sigma T_s^{*4} + k_s \frac{T_F}{\Delta x} \Big|_s}{-k_g \frac{T_s}{\Delta x} \Big|_g + 4\varepsilon_s \sigma T_s^{*3} + k_s \frac{T_s}{\Delta x} \Big|_s} \quad (4)$$

where  $T_F$ ,  $k_g$ ,  $k_s$ ,  $\sigma$  and  $q_{in}$  are furnace temperature, thermal conductivity of the gas and steel, and Boltzmann's constant, respectively. Asterisk \* and  $s$  denote previously-calculated surface temperature, steel and furnace wall, and the incoming heat by radiation, respectively.

Boundary condition 2 represents the adiabatic type of boundary condition where the surface is totally insulated. For this case (2) becomes:

$$(1 + 4F_0)T_{(n,m)}^{p+1} - F_0(2T_{(n+1,n)}^{p+1} + T_{(n-1,m)}^{p+1} + T_{(n,m-1)}^{p+1}) = T_{(n,m)}^p \quad (5)$$

Boundary condition 3 represents heat of convection by the cooling water flowing in the cooling pipe. It is effected by a number of parameters such as the cooling water temperature, convective heat transfer coefficient, which, in turn, is affected by water flow rate and thermal properties. For the reason that these parameters are difficult to measure for such a big water cooling system with many pipes running across and along the furnace, the internal surface temperature of the cooling pile is assumed to be constant at a value of 50 °C. This assumption should not pose any problems in the results since the exit cooling water temperature is about 40 °C and relative temperature values are sought in these calculations.

### C. Input Parameters

The system of equation generated by the system configuration shown in Fig. 2 is solved by constructing a Fortran program using Compaq Visual Fortran package with a Compaq Array Viewer for output plotting. The parameters used in the calculation are presented in Table 1.

TABLE I: PARAMETERS USED IN CALCULATING THE TEMPERATURE DISTRIBUTION IN THE STEEL SLAB [8].

Parameter	Symbol	Value	Units	Remarks
Steel Density	$\rho$	7600	kg m <sup>-3</sup>	Refs. 7,8
Steel thermal capacity	$C$	456	J kg <sup>-1</sup> K <sup>-1</sup>	
Steel thermal conductivity	$k_s$	80	W m <sup>-1</sup> K <sup>-1</sup>	
Steel emissivity	$\varepsilon_s$	0.5	No dimensions	
Furnace wall emissivity	$\varepsilon_w$	0.85		
Gas thermal conductivity	$k_g$	10 <sup>-2</sup>	W m <sup>-1</sup> K <sup>-1</sup>	
Space interval	$\Delta x$	0.25	cm	
Boltzmann's constant	$\sigma$	5.669 x 10 <sup>-8</sup>	W/m <sup>2</sup> K <sup>4</sup>	common
Calculation time interval	$\Delta t$	0.04	s	
Furnace temperature	$T_F$	Shown in Table 2	°C	°K in equations

From the steel discharge rate and furnace total load, the moving speed of the slab through the furnace was

determined, and hence, slab residence time in each zone was specified as given in Table II. Using this information along with the temperature set points of each zone, slab temperature trends along the furnace were evaluated.

TABLE II: FURNACE APPLIED RESIDENCE TIMES AND TEMPERATURE SET POINTS IN REHEATING THE STEEL SLAB [8].

Zone	Length (m)	Slab Residence Time (min)	Zone Set Temperature (°C)	
Charge	7	35	900 (from passing hot gases)	
Preheat	Top	8	40	1270
	Bottom			1270
Heating	Top	8	40	1260
	Bottom			1250
Soak	7	35	1250	

### III. RESULTS AND DISCUSSION OF RESULTS

Temperature distribution in the slab was calculated and the results are presented by different plots. Fig. 4 shows temperature height plots throughout the slab where the temperature behavior in the area affected by the skid touching the bottom surface of the slab can be seen. From this figure and for different skid heights, the effect of decreasing the skid height on the temperature in the area near where the skid touches the slab is very clear. The different skid heights represent skid wear out due to the movement of the slabs on the skids, and hence, decreases in height gradually. It can be seen that a temperature dip occurred at the centre of the contact area between the skid and the slab. This temperature dip increases with decreasing skid height.

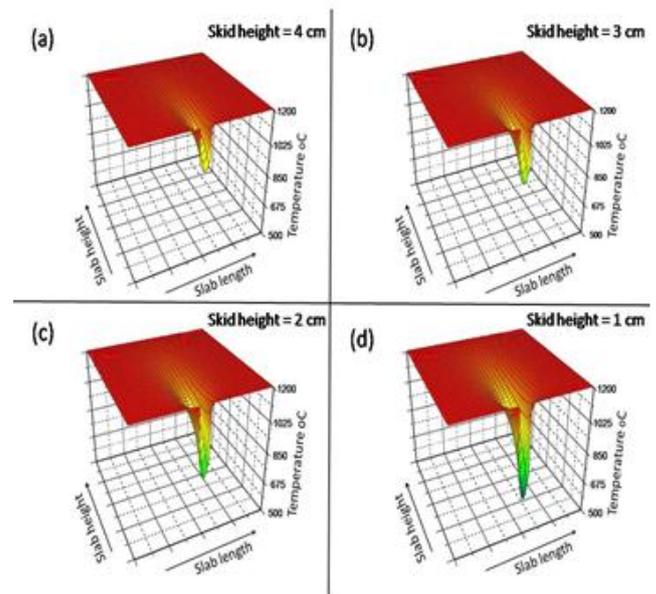


Fig. 4. Temperature height plots of the slab at furnace exit for skid heights of: (a) 4 cm, (b) 3 cm, (c) 2 cm, (d) 1 cm.

Image plots of the temperature distribution in the slab are shown in Fig. 5 for the different skid heights. It can be seen from this figure that the affected area due to decreasing skid heights increases in all directions, i.e., in height and width, as skid wear increases due to shear stress caused by slab slide on the skids. For the minimum skid height of 1 cm slab temperatures near the contact areas show a big decrease reaching approximately the center line of the slab height.

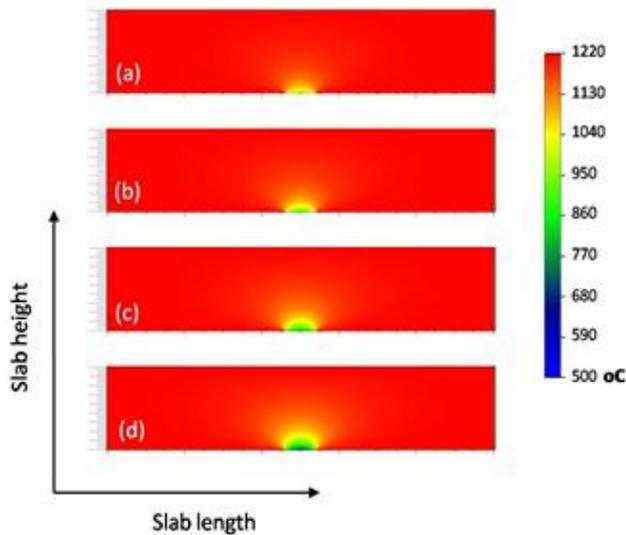


Fig. 5. Temperature image plots of the slab at furnace exit showing low temperature areas at the slab-skid contact for skid heights of: (a) 4 cm, (b) 3 cm, (c) 2 cm, (d) 1 cm.

The maximum temperature differences, due to heat loss through the skids, between the point of contact of the skid and the slab and slab top surface are shown in Fig. 6. For a skid height of 1 cm, the maximum wear considered, a temperature difference of approximately 500 °C is calculated. For no skid wear, i.e., a maximum skid height of 4 cm, a temperature difference of approximately 200 °C is found.

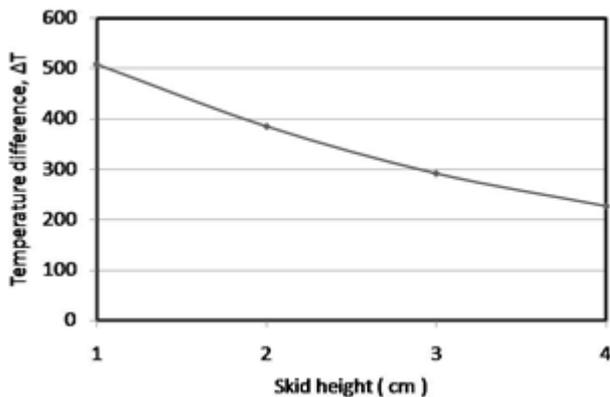


Fig. 6. Maximum temperature difference profile between the point of contact of skid and slab and slab top surface for different skid heights.

Temperature profiles along slab height extending from the center of the skid-slab contact area are shown in Fig. 7 for the four skid heights. The figure shows that the bottom first quarter of the slab is affected extensively by the heat sink due to the skid heat withdrawal. This observation is more pronounced for skid heights of 2 and 3 cm.

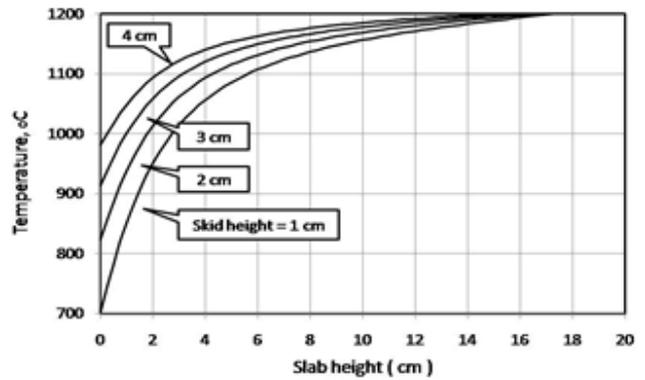


Fig. 7. Temperature profiles at the furnace exit along slab height from the center of the skid-slab contact area for different skid heights.

The temperature dip in the area of the skid-slab contact, due to heat withdrawal through the skid, was looked at in terms of maximum temperature decrease from the slab top surface and its profiling along the slab height above the location of the skid. However, the width of the area effected by the heat withdrawal for the different skid heights is shown in Fig. 8. It can be seen that the maximum width of area effected where temperature dip exists is about 18 cm at its maximum and decreases to about 4 cm near the centre of the slab. There is little difference in this width for the different skid heights.

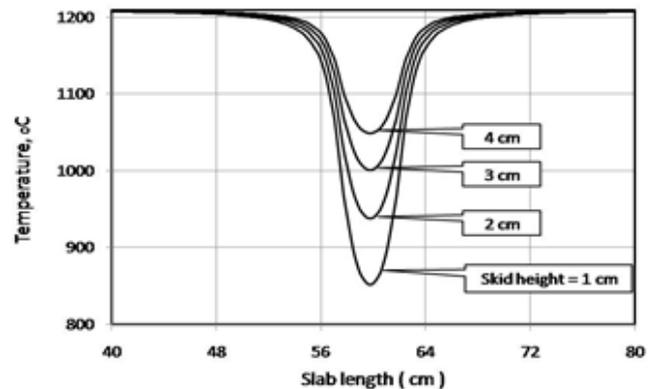


Fig. 8. Temperature profiles at the furnace exit along the slab length at a distance of 1 cm from the slab surface for different skid heights.

The above results show that due to the contact between the skid and the slab bottom surface there is a considerable temperature drop in this contact area. This temperature decrease is more considerable when the skid height decreases due to skid wear where the maximum temperature decrease (from slab top temperature) was found to be about 500 °C. This temperature decrease area extends to about half the slab height. From the figures it was seen that the width of the area affected by this temperature drop is about 10 cm. The contact area between the slab and the skid extends across the slab in three locations. Hence, the effect is considerable. The mechanical properties are a function of temperature, and hence, the slab upon rolling will not be homogeneous in mechanical properties. Rolling will create the steel to enlarge lengthwise, and since the maximum temperature drop is at the slab surface, the surface layer will be different in mechanical properties compared to the rest of the material of the slab.

## IV. CONCLUSION

This study on the effect of skid wear out on the temperature distribution in the area surrounding the slab-skid contact during the reheating of steel slabs in pusher-type furnaces, showed considerable temperature drop due to skid water cooling. This temperature drop extended to about half height of the slab and about 10 cm in width. The maximum temperature drop for the maximum skid wear out of 3 cm was calculated to be about 500°C from the maximum slab reheating temperature of about 1230°C. It is highly recommended in this work that skids used in reheat furnaces should not be extended in their use and be replaced before reaching minimum height in order to ensure thermal homogeneity of the slabs before hot rolling.

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