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Simulation of Temperature Distribution in a Continuous Tunnel Reheat Furnace Using the Monte Carlo Method

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Abstract

A mathematical model of a continuous reheating furnace has been developed to identify the design and operating parameters that significantly affect furnace performance. In this study, the furnace is modeled 3 dimensionally and the Monte Carlo method is used to find the overall absorption factor. The overall absorption factor is then used to calculate the energy balance for furnace walls, the gas, and the moving slab. For this purpose, 1-D heat conduction in walls and 2-D heat transfer in the slab are assumed. Results include temperature distribution of gas, walls, and slab. The effects of emissivity of slab and furnace height on the efficiency of furnace are also analyzed. It is concluded that operating efficiency increases by increasing load emissivity and by decreasing furnace height.

Keywords: Overall absorption factor, Tunnel reheat furnace, Monte Carlo Method, Radiative heat transfer.

Symbols

A_i	Surface area of element i (m^2)
a_i	Gas absorptivity (m^{-1})
$B_{si,sj}$	Energy fraction emitted from surface element i and absorbed by surface element j to total emission from surface element i
$B_{gi,sj}$	Energy fraction emitted from gas element i and absorbed by surface element j to total emission from gas element i
$B_{gi,gj}$	Energy fraction emitted from gas element i and absorbed by gas element j to total emission from gas element i
C_p	Specific heat capacity (J/Kg.K)
g_i	Gas element i index
h	Convective heat transfer coefficient (W/m^2)
$k(T)$	Coefficient of thermal conductivity versus temperature (W/m.K)
$\dot{m}$	Mass flow rate inside furnace (kg/sec)
N_g	Total number of gas elements inside furnace
N_s	Total number of surface elements inside furnace
$Q_{combustion}$	Heat generated inside gas elements due to combustion (W)
Q_{in}	Heat input to moving slab (W)
Q_{out}	Heat dissipation by conduction out of furnace (W)
r_i	Inner polar element boundary (m)
r_o	Outer polar element boundary (m)
r_p	Emission distance from center in polar coordinate (m)
R_r, R_φ	Random numbers
T_a	Ambient temperature (K)
T_{gi}	Gas element temperature (K)
T_{si}	Surface element temperature (K)
T_{ref}	Reference Temperature for enthalpy measurement (K)
U_i	Total heat transfer coefficient of walls (W/K)
V_i	Volume of gas element i (m^3)
x	Horizontal distance (m)
y	Vertical distance (m)
ε_i	Surface element *i* emissivity coefficient
(θ, φ)	Polar coordinate of emission (Rad)
ρ	Density (Kg/m^3)
σ	Stephan Boultzman constant ($W/m^2.K^4$)

Introduction

The preheat furnace is one of the primary components of the hot rolling process, which is used to set the temperature of the slab to a certain value and keep it evenly distributed. This paper presents a mathematical model of a continuous reheat furnace. The model was developed to identify the design and operating parameters that significantly affect the furnace performance. There are different methods to investigate radiative heat transfer inside the furnace. One can write energy balanced equations coupled with radiative heat transfer as a source term and solve it by discrete ordinate method (1) or consider complete

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fluid motion with turbulence and chemical reaction and solve it by such commercial software as Fluent 2). The advent of tunnel furnaces, as we know them today, began in 1989 when the first thin-slab casting facility was commissioned at Nucor Steel's Indiana facility 3). In the absence of detailed data of gas velocity field inside the furnace, CFD modeling of convective heat transfer would not be more reliable than using convective formulas proposed in the literature 4). Since radiation is the dominant heat transfer mode inside the furnace, accounting for 90 percent of all thermal exchange 5), Newton's law of cooling is preferred with a nearly accurate radiation model. From among the different methods of solving radiative heat transfer inside the furnace, the Monte Carlo method is selected in this study. It uses discrete photons and traces them until absorbed by the gas inside or by one of the surfaces. This approach is thoroughly statistical.

Methodology

In order to formulate the total energy equation inside the furnace, overall absorption factors need to be calculated 6). With respect to uniformity of radiative heat flux of surfaces and its diffusivity, it is assumed that single photons with identical amounts of energy are emitted and that the numbers of photons increase to ensure continuity of emissions. As a ray enters a gas medium and moves inside it, part of its energy is absorbed by the gas, another part may be scattered in the gas, and the remaining continues its way until it reaches one of the surface elements. This portion of the energy may be absorbed by the surface (diffuse or specular), reflected, or may pass through the surface. In order to calculate the overall absorption factors by tracing a huge number of rays, we need to know how to select a set of rays statistically and how to select for each ray a point of emission, direction, and wavelength of trigger 7). It is then that a decision can be made whether a single photon is absorbed or reflected. Using the Monte Carlo statistical approach, the point of emission on a surface in a polar coordinate could be defined as 8):

$$r_P = \sqrt{r_i^2 + \left(r_o^2 - r_i^2\right)R_r} \tag{1}$$

$$\varphi_P = 2\pi R_\varphi \tag{2}$$

Where R_r and R_φ are random numbers. Also direction of emission (θ, φ) could be determined as in the following formula 8), in which θ is measured from local z axis and φ is its projection on local xy plane, measured from x axis.

$$\theta = \sin^{-1}\sqrt{R_\theta} \tag{3}$$

$$\varphi = 2\pi R_\varphi \tag{4}$$

For the emission of a gas element, the direction of emission is 8):

$$\theta = \cos^{-1}(1 - 2R_\theta) \tag{5}$$

$$\varphi = 2\pi R_\varphi \tag{6}$$

This direction is the same as that for back-scattering from gas. If a photon reaches an element, we can determine whether this photon is absorbed or reflected by assigning fixed values of absorptivity and reflectivity, and then by comparing a random number in each step with these values. The overall absorption factors could be obtained by dividing the total absorptions (i to j) to the total emissions from the element i. As discussed above, overall absorption factors can be determined using the Monte Carlo method. To find temperatures both inside the furnace and in the moving slab, the overall energy balance should be written. For each surface element, i, the energy balance will be 9):

$$\sum_{j=1}^{N_S} \sigma\varepsilon_i A_i B_{si,sj} T_{sj}^4 + \sum_{j=1}^{N_g} \sigma\varepsilon_i A_i B_{si,gj} T_{gj}^4 - \sigma\varepsilon_i A_i T_{si}^4 + hA_i\left(T_{gk} - T_{si}\right) - Q_{out} = 0 \tag{7}$$

Where, Ns is the total number of surface elements and Ng is the total number of gas elements. The first and second terms on the left hand side show total absorption by other surfaces and gas elements. The third term is the emission out of the surface while the fourth term is the net convective exchange. The last term is heat dissipated by conduction out of the furnace, which could be calculated as follows:

$$Q_{out} = U_i\left(T_{si} - T_a\right) \tag{8}$$

Where, U_i is the total heat transfer coefficient of the wall. A similar expression may be applied for the moving slab 9):

$$Q_{in} = \sum_{j=1}^{N_S} \sigma\varepsilon_i A_i B_{si,sj} T_{sj}^4 + \sum_{j=1}^{N_g} \sigma\varepsilon_i A_i B_{si,gj} T_{gj}^4 - \sigma\varepsilon_i A_i T_{si}^4 + hA_i\left(T_{gk} - T_{si}\right) \tag{9}$$

This is the same as Equation (7), except heat dissipation is ignored in this one. For the gaseous element, the energy conservation equation yields 9):

$$\begin{aligned} &Q_{combustion} + \sum_{j=1}^{N_S} 4a_i\sigma_i B_{gi,sj} V T_{sj}^4 + \sum_{j=1}^{N_g} 4a_i V_i B_{gi,gj} \sigma T_{gj}^4 - 4a_i V_i \sigma T_{gi}^4 \\ &- \sum_{j=1}^{k} A_i h_j\left(T_{gi} - T_{sj}\right) + \dot{m}C_P\left(T_{gi+1} - T_{ref}\right) - \dot{m}C_P\left(T_{gi} - T_{ref}\right) = 0 \end{aligned} \tag{10}$$

Where, $Q_{combustion}$ is heat due to combustion and the two last terms show changes in energy because of mass inlet and outlet. Temperature distribution in the slab is obtained by solving Equation (11) 10):

$$\rho C_p\left(V_L \frac{\partial T}{\partial x}\right) = \frac{\partial}{\partial x}\left(k(T)\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k(T)\frac{\partial T}{\partial y}\right) \tag{11}$$

Where, V_L is the speed of slab in the furnace and k (T) is its conductivity. By assuming a temperature distribution inside the furnace and using Monte Carlo method, heat input on the surface of the slab could be found. Then equation (11) is solved using an iterative method (such as steepest descent) to determine two dimensional temperature distribution inside slab. Surface temperature of the slab is considered as the lower wall temperature of the furnace and equations (7), (10) are solved simultaneously to find other surface and gas element temperatures. This process continues until the iterative method converges. Figure (1) shows a schematic view of a furnace. The boundary conditions for solving Equation (11) include uniform temperature in the furnace inlet and upper radiative and convective heat flux. As a result of the low gas temperature at the upper and lower sections of the furnace (50°C, as reported by MSC), the slab could be taken to be symmetrical along with its half thickness, and its mid line to be adiabatic.

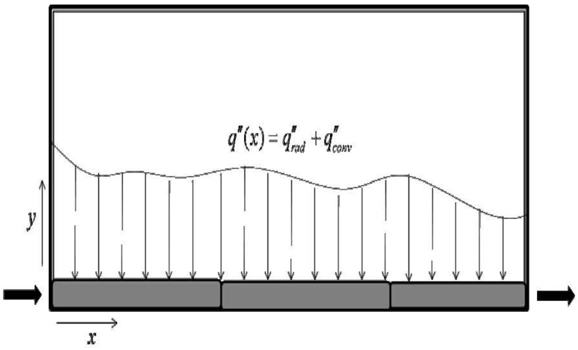

Fig. 1. Schematic view of the modeled reheat furnace.

Results

The furnace under study is the heating section of Saba tunnel reheating furnace at Mobarakeh Steel Complex (MSC). The parameters used in this simulation are listed in Table 1. A simulator program was written using MATLAB. Two meshes were used in the modeling, one (coarse mesh) for the furnace with 1002 elements and the other (fine mesh) with 3200×5 elements, to determine temperature distribution in the slab. By further refinement of the mesh size, it is validated that this mesh size ensures mesh independency. Validation of the model was accomplished using real gas temperatures reported by Mobarakeh Steel Complex, Saba Steel, and slab surface and core temperatures reported by Danieli level 2 control system, which showed 0.5 to 10.5% deviations in different sections. Five million rays per each surface element were used to find the overall absorption factor inside the furnace. Reducing the emitted optical rays (photons) up to one million rays did not lead to considerable changes in problem accuracy. Further reduction caused more fluctuations around the accurate solutions (Figure 2).

Figure 3 shows both measured and calculated gas temperatures inside the furnace. Calculated temperatures are for two different slab surface emissivities. As shown, there is a good match between the measured and calculated variables in the first half of the furnace. But the difference is greater at the end of the furnace. According to this figure, minimum deviation between measured and calculated gas temperatures inside the furnace is 0.5% for $\varepsilon_L = 0.8$ and 1.1% for $\varepsilon_L = 0.6$ at a distance *x=29.45*. However, it increases to 7.4% for $\varepsilon_L = 0.8$ and to 10.1% for $\varepsilon_L = 0.6$ at the end of the furnace (*x=97.8 m*). Jannesari and Saboonchi [11] used the Monte Carlo method and reported a difference of 5 to 35 percent between the real and calculated gas temperature values for a power plant boiler at different heights. So this method may contain severe deviations from real gas temperatures. As predicted, the turbulence in velocity field inside a boiler is more significant than in a reheat steel furnace. Figure 4 shows the change in the load surface temperature with varying load emissivity values. The remaining furnace parameters were as reported in Table 1. As ε_L increases from 0.1 (reflective surface) to 1.0 (black body), larger amounts of radiant energy are absorbed at the load surface, resulting in higher load surface temperatures. Since the additional heat transferred to the load is removed from the combustion gases, lower gas temperatures are expected (Figure 5).

Table 1. Base furnace parameters used for the parametric study.

Furnace dimensions	100*0.8*2 (m^3)	Fuel	Natural Gas
Fuel consumption	880-635 m^3/hr	Gas input at each burner	26m^3/hr
Natural gas heating value	9200 kCal/m^3	Number of burners	39+39 (Left and Right)
Air fuel ratio	10	Preheat air temperature	470°C
Cold roller speed	2.5-45 m/min	Slab material	Carbon Steel
Slab specific heat	1169 J/kg.K	Slab density	9850 W/m.K
Thickness	50 mm	Slab conductivity	31W/m.K
Wall refractory thickness	275 mm	Refractory overall heat conductance	0.96 W/m^2K
Roof refractory thickness	230 mm	Roof refractory overall heat conductance	3.48*10^{-3} W/m^2K
Gas absorptivity	0.175 m^{-1}	Convective heat transfer coefficient	50 W/m^2K

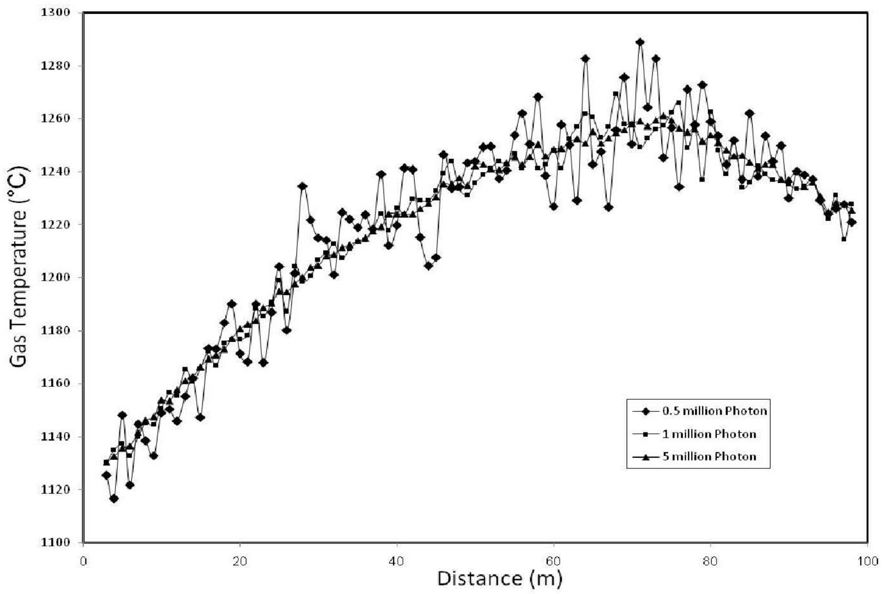

Fig. 2. Gas temperature inside the furnace at different emitted rays through the furnace.

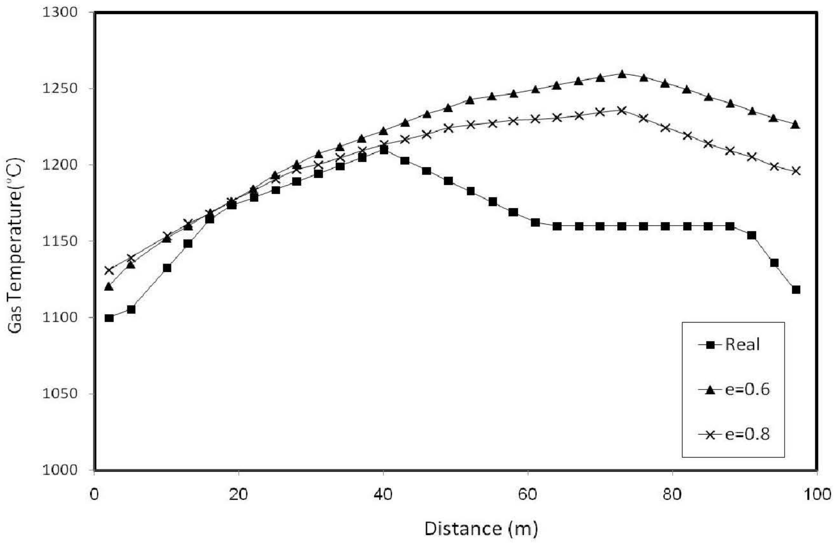

Fig. 3. Experimental data by Mobarakeh and Danieli.

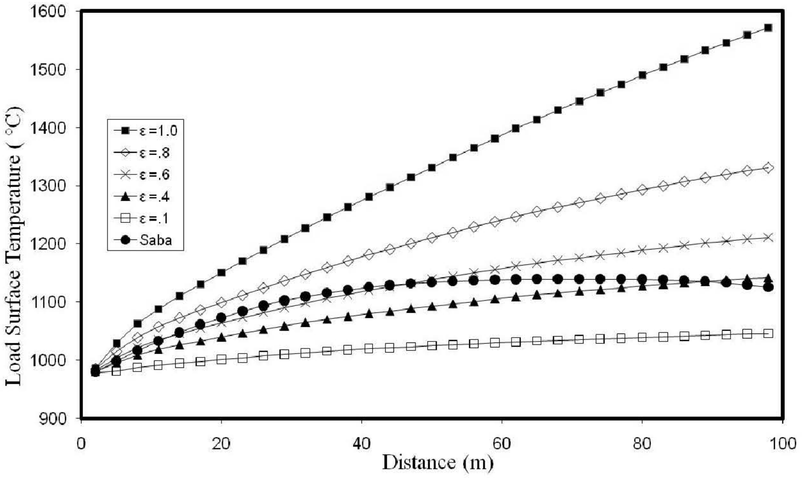

Fig. 4. Load surface temperature as a function of load emissivity and distance through the furnace.

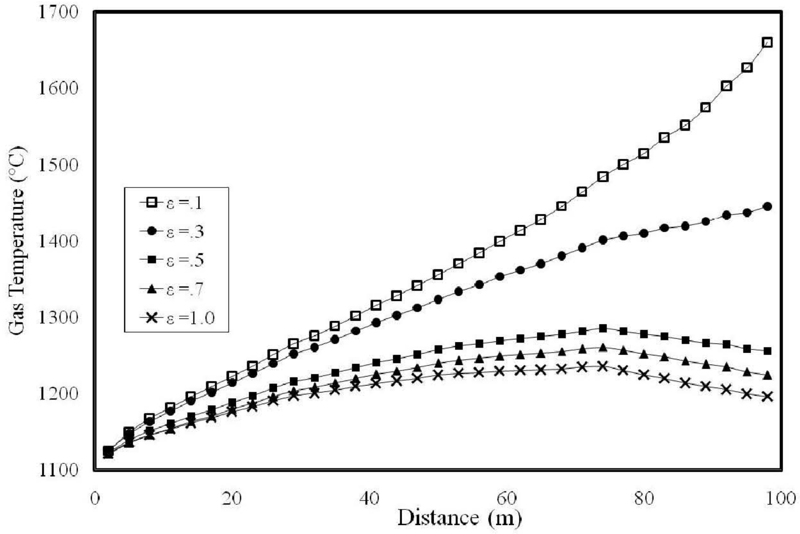

Fig. 5. Combustion gas temperature as a function of load emissivity and distance through the furnace.

The height of the furnace combustion space was increased from 0.6 m to 1.0 m. The remaining furnace parameters were as stated in Table 1. The load surface temperature decreased as the height of the combustion space increased (Figure 6). This trend is due to the decrease in gas temperature with increasing combustion height, as shown in Figure 7. The temperature of the combustion gases decreases since the surface area of the refractory increases with increasing combustion space height. This increase in refractory surface area increases the radiative and convective heat transfers from the gases to the refractory side walls, leading to an increase in the amount of energy that is transferred through the refractory to the ambient air. As the slab moves toward the end of the furnace, it absorbs more heat flux in the furnace and its temperature increases. As mentioned above, increased slab surface emissivity causes its surface temperature to increase (Figure 8), and if a constant temperature is desired at the exit, the firing rate must be lowered (positive effect). However, this causes the amount of unfavorable temperature gradient also to increase (negative effect). Hence, there should be an optimum point. Another point to be noted here is that surface emissivity is more effective when it increases over the range from 0.6 m to 1.0 m than its increasing over the range from 0.1 m to 0.6 m. As shown in Figure 9, it is evident that the effect of decreasing combustion height on slab temperature increments is greater than its unfavorable temperature gradient. Hence, it seems that reducing the combustion height is more effective than increasing slab emissivity.

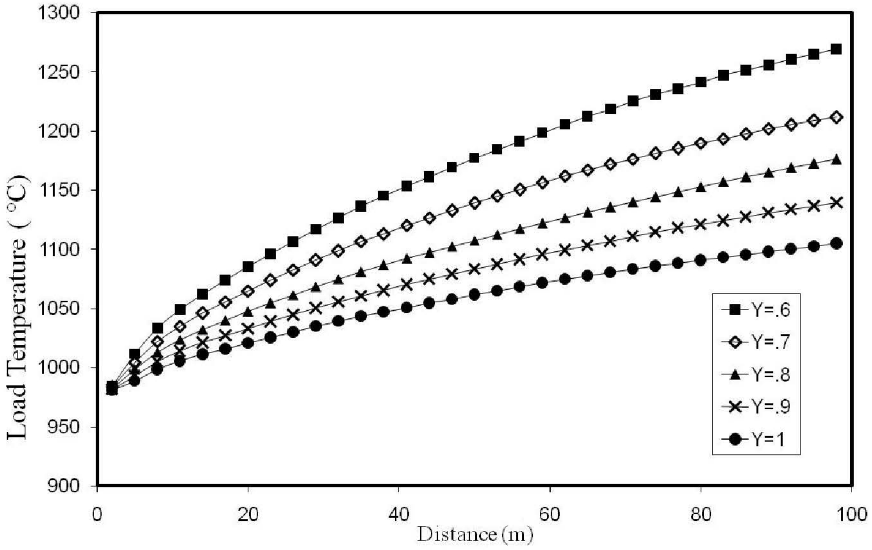

Fig. 6. Load surface temperature as a function of combustion space height and the distance through the furnace.

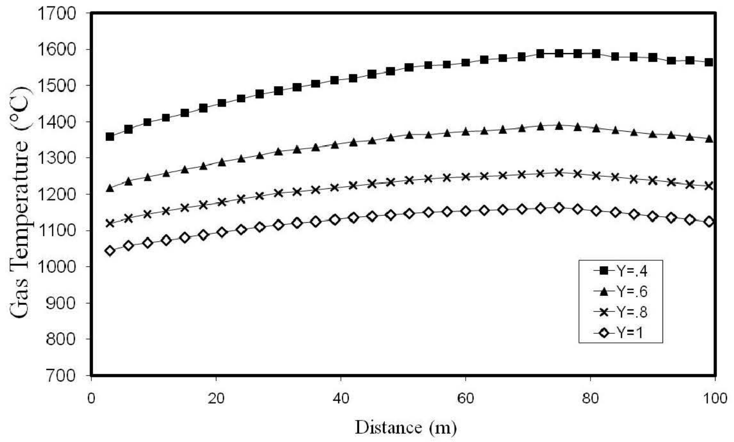

Fig. 7. Combustion gas temperature as a function of load emissivity and distance through the furnace.

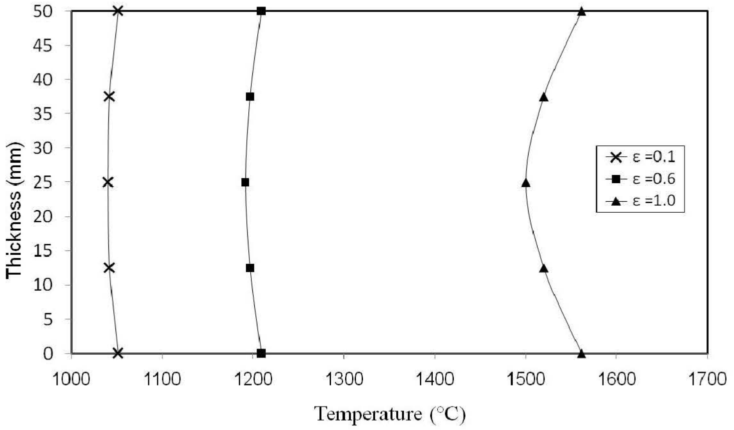

Fig. 8. Temperature profile inside the slab at x=100 (m) as a function of load emissivity.

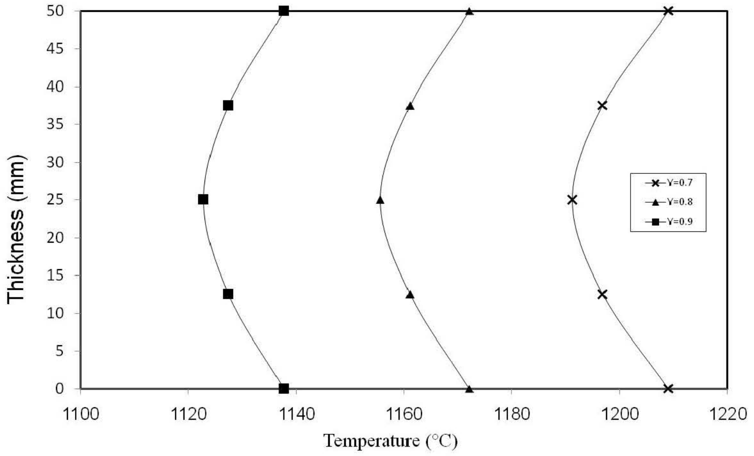

Fig. 9. Temperature profile inside the slab at x=100 (m) with $\varepsilon_L = 0.6$ *as a function of combustion height.*

Conclusions

- In this paper, efforts were made to find a model which is simple and accurate enough to be used as a real time thermal model for Saba Tunnel Furnace level 2 automation system. The Monte Carlo method was found to be a good candidate as it is easy to use in complex geometries. Additionally, it is capable of calculating the overall absorption factor in one swoop for low temperature changes.
- As shown in Figure 6, the furnace efficiency decreases by increasing the height of the furnace combustion space above the load. By increasing furnace height from Y=0.6 to Y=1.0, slab surface

temperature at furnace exit decreases from 1260˚C to 1096˚C, which shows a decrease of 13% in furnace efficiency.

- The furnace efficiency increases substantially by making the load approach a radiatively black surface (Figure 5). As shown in Figure 4, by increasing load emissivity from $\varepsilon_L = 0.1$ to $\varepsilon_L = 1.0$ (black surface), the exit load surface temperature increases from 1026˚C to 1582˚C, which is a 54% increment in efficiency. This improvement can be easily accomplished by coating the load surface with a material such as graphite.
- The modeling of a continuous reheating furnace showed its usefulness in facilitating the process of designing a new furnace or of optimizing the operating parameters for the Saba Tunnel Furnace or similar tunnel furnaces.

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