

# The study of heat transfers in heat treatment furnaces in steel industry

N Rezazadeh<sup>1,2</sup>, H Hosseinzadeh<sup>2</sup> and B Wu<sup>1</sup>

1. National Research Centre of Pumps, Jiangsu University, Zhenjiang, China

2. Department of Mechanical Engineering, Hakim Sabzevari University, Sabzevar, Iran

akrezazadeh@yahoo.com

**Abstract.** In present work, heat transfer in heat treatment furnaces in steel industry was studied experimentally and numerically. Ansys - Fluent has been used for numerical simulation. Ansys - Fluent solvers are based on the finite volume method. Furnace geometry of numerical simulations was based on the size and dimensions of heat treatment furnace located in Esfarayen Steel Plant where experimental data have been measured. First, the evaluation of three two-equation turbulence models accompanying with experimental results were examined. The results of this study showed that the Realizable k- $\epsilon$  model, could predict load center line temperature better than the other two models in different times, and it is more agreed in comparison to experimental data. Second, due to study the radiation effect in numerical simulation, it was revealed that results, in a maximum error mode, showed the temperature difference 3°C in a state without radiation to the experimental data, but this difference maximum was reduced to 2°C by using the modified simulation model of radiation and got improved 33% for the numerical simulation in comparison with experimental data.

## 1. Introduction

Performance of treatment furnaces could be improved by proving the less temperature difference in the load charged at the furnace over time. The other important term is the energy consumption. Heat treatment furnaces in steel industries have the highest consumption after melting furnaces and this is why so many studies have been concerned about on heat transfer in furnaces. Dosset and Boyer [1] presented the principles of steel heat treatment. Keramida et al. [2] studied the discrete radiation transfer model in a natural gas-fired furnace. They developed their work of discrete transfer radiation model and assessed the model radiation six-flux [3]. White and Probert [4] studied the forced convective heat transfer in furnaces for heat treatment and found that the vertical space between the billets is effective parameters in force convection of billets. Sompong and Angkurn [5] simulated the natural convection in a complicated enclosure with two wavy vertical walls. They investigated the effect of variation of Darcy and Raily numbers on the temperature distribution, and heat transfer inside the enclosure. Lari et al. [6] studied radiation and natural convection heat transfer in a square cavity in a wide range of Raily numbers  $10^2$ -  $10^6$  and the thickness of the optical 0 -100. Kang and Rong [7] conducted a research in the field of modeling and simulation of heat load on the furnace heat treatment. Tagliafico and Senarega [8] performed a two-dimensional transient simulation of heat for empty and solid cylinders in heat treatment furnaces using finite difference method. Anderson and Martin [9] simulated the energy balance in heat treatment furnaces and compared the simulated temperature profile for combustion



chamber with experimental temperature. Kim [10] considered the transient heating load in reheating furnace, for different parameters such as absorption and emission factor. Khoukit and Tangthieng [11] performed a numerical investigation for the temperature uniformity of a billet based on thermal radiation in a reheating furnace. Dubey and Srinivasan [12] studied the billets transmission in the field of transient heat transfer, verified the lost energy during the certain product rate, and found that most of the energy was lost by radiation in the process of transferring billets. It was also revealed that the wasted radiation heat can be reduced by reduction the transfer time, increasing speed of billets, and covering them with a duct to reduce radiation from the billets surface. Zhang et al. [13] analysed the three-dimensional transient heat transfer in a pre-heating furnace in a hot roll mill. Jung et al. [14] and, Lee and Kim [15] investigated the effects of the wall and load emissivity and residence time in the furnace to predict temperature profiles and its impact on the steel load heating. They found that temperature difference is reduced by increasing the residence time. Wu1 et al. [16] simulated the heat transfer in continuous heat treatment furnace and examined the effect of the pattern and movement speed of the load in the heating processes in the furnace. Minya [17] considered the numerical simulation and experimental validation of the enhanced heat transfer in a heat treatment furnace, and found out, generally, thermal temperature depends on the position of the radiation panels. Champan et al. [18] studied the effective parameters such as the load heat capacity, the load emissivity and the rate of fuel combustion, respectively, on heat transfer in a pre-heating direct-fired furnace. Jang et al. [19] predicted the thermal characteristics of the load in preheating furnaces with the formation and growth of oxides on the surface of the load.

In present work, to obtain the realistic investigation compared the experimental data, three dimensional model of heat treatment furnace is simulated using the appropriate turbulence model. Firstly, the best turbulence model concerning the two-equation models is presented and secondly, considering the radiation in the numerical simulation of heat transfer improves the CFD data in comparison the experiment data.

## 2. Experimental tests

All experiments were performed in Steel Industries and included measuring the temperature of loads during preheat in furnace that will be discussed in more detail in following section. Internal dimensions of furnace  $9 \times 3.4$  m and height of the boggy surface up to the furnace roof is 2.2m. A view of the studied heat treatment furnace can be seen in figure 1.

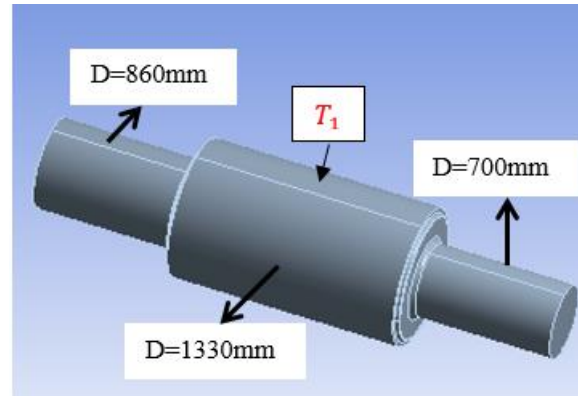


**Figure 1.** View of a heat treatment furnace.

This furnace is rectangular and includes 12 burners which there are 6 burners in each its longitudinal side. In this study, target load geometry is carbon steel.

Target load geometry in this study is an axis shown in figure 2. The burners' model of the studied furnace are 3640-HS HSDF-R. K thermocouple is used for measurement in this study. Operating temperature

range of between  $-200\text{ }^{\circ}\text{C}$  and  $1350\text{ }^{\circ}\text{C}$  (this range is not absolute and will vary depending on the manufacturer and type of appearance). In K -Thermocouple, copper has been used for anti-oxidation that seems appropriate due to the oxidation which occurs in the furnace.



**Figure 2.** Load geometry and location of temperature measurement during test.

The physical properties of carbon steel used in the simulation are also in table 1.

**Table 1.** Physical properties of carbon steel.

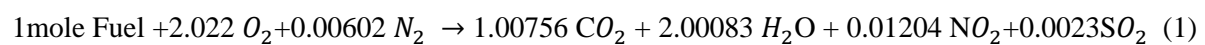
$k(W/m\ k)$	$C_p(j/kg\ k)$	$\rho(kg/m^3)$
52	486	785.

### 3. Numerical simulation

#### 3.1. Governing equations

Important issues that occur in relation to the process of the furnaces and burners are divided into two main sections of chemical reactions and fluid flow equations:

**3.1.1. Combustion chemical reactions.** The overall reaction of burning one mole of the feeding gas of the furnace is presented as following equation (1):



The amount of required air for burning one mole of gas is calculated as below:

$$2.022 \times 1/0.21 = 9.6285 \text{ mole of Air}$$

$$(Air/Fuel)_{mole} = 9.6285$$

According to gas analysis, molecular mass of gas is 16.4378 and molecular mass of air is 28.97, as a result, the air-fuel ratio in terms of mass is:

$$(Air/Fuel)_{mass} = (9.6285 \times 28.97)/(1 \times 16.4387) = 16.9684$$

In practice, some excess air is always necessary for complete combustion that is normally 10% of the air volume which is calculated theoretically for gases, so:

$$\text{Excess Air} = 9.6285 \times 0.1 = 0.96285$$

$$(Air/Fuel)_{mass} = 16.9684 + 0.96285 = 17.93125$$

This means that in the operating conditions, for burning a 1kg of fuel, 17.93kg of air is required while this amount is 8.76kg in real conditions, of furnace during tests.

**3.1.2. Equations of fluid flow.** Continuity and momentum equations must be solved for fluid flow field, and due to heat transfer, the energy equation should be added. These equations are indicated for three-dimensional, steady and incompressible flows by applying the average time properties of turbulent flow which are expressed respectively as follow [20]:

$$\nabla \cdot (\rho \vec{V}) = 0 \quad (2)$$

$$\frac{\partial}{\partial t} (\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot (\bar{\tau}) + \rho \vec{g} + \vec{F} \quad (3)$$

Where is P fluid pressure,  $\vec{F}$  vector sum of the body forces and  $\bar{\tau}$  is the stress tensor. Energy equation is expressed as following:

$$\frac{\partial}{\partial t} (\rho E) + \nabla \cdot (\vec{v} (\rho E + p)) = \nabla \cdot (k_{\text{eff}} \nabla T - \sum_i h_i \vec{J}_i + (\bar{\tau}_{\text{eff}} \cdot \vec{v})) + S_h \quad (4)$$

The first three terms on the right-hand side of equation (4), represent energy transfer due to conduction, species diffusion, and viscous dissipation, respectively. And where  $k_{\text{eff}}$  is the effective conductivity ( $k + k_t$ ) where  $k_t$  is turbulent thermal conductivity and is defined according to the turbulence model being used, and  $S_h$  includes the resulted heat of the chemical reaction.

**3.1.3. Turbulence models.** Regarding the fact that the flow is turbulent in the burner, thus it would be necessary that the turbulence equations to be solved. In this research, only two-equation turbulence models included Standard k- $\epsilon$ , Realizable k- $\epsilon$  and RNG k- $\epsilon$  were studied due to optimization of the computation time.

**3.1.4. Combustion simulation.** In order to simulate the combustion, the species transport model has been used. In this model, a transport equation for each species (in these four equations) dissolved and in each round, mass fraction is calculated. This method ignores the middle reactions, radicals, and other additional products of combustion. So, having an acceptable accuracy is affordable in term of computational cost. Transport equation is as following relation (15):

$$\frac{\partial}{\partial t} (\rho Y_i) + \nabla \cdot (\rho \vec{v} Y_{i\vec{v}}) = -\nabla \cdot \vec{J}_i + R_i \quad (5)$$

$\vec{J}_i$  is mass diffusion term in turbulent flows and are defined as follows:

$$\vec{J}_i = -\left(\rho D + \frac{\mu_t}{Sc_t}\right) \nabla Y_i \quad (6)$$

Where D is species diffusion coefficient and  $Sc_t$  is turbulent Schmidt number. Energy source of the chemical reaction is as follows:

$$S_h = - \sum_i \frac{h_i^0}{M_i} R_i \quad (7)$$

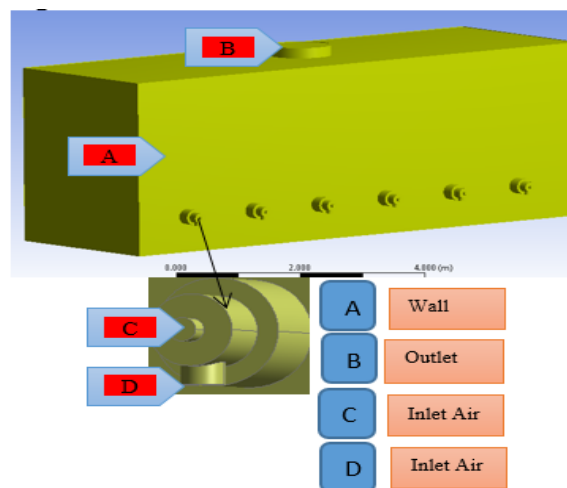
$h_i^0$  production Enthalpy of species i and  $R_i$  is generated molar rate species j this energy source produced is put directly at the energy equation [20].

**3.1.5. Radiation.** IN the furnace, radiation is considered as the most important heat transfer method from the flame to the environment because of its very high temperature.

To calculate the radiation, the radiative intensity transport equation is solved. Radiative intensity transport equation (RTE) for an absorbing, emitting and scattering medium in position  $\vec{r}$  and direction  $\vec{s}$  is as [20].

### 3.2. The initial and boundary conditions

Required air of burners will be supplied by a blower, and the blown air is exchanged with exhaust heat from the furnace before entering the burners, and the air temperature will be 50 °C while the gas temperature is 35 °C. Blower capacity is 2940m<sup>3</sup>/h and given the number 12 burners, each burner capacity is 245.66m<sup>3</sup>/h, and burners' aerated pipe diameter is 0.065m, therefore, the considered inlet air velocity for each burner is 20.5m/s. The amount of gas consumption for each burner 110Nm<sup>3</sup>/h and due to the gas inlet pipe diameter of 0.04m, the speed of inlet gas is 9.2m/s and, because furnace walls in real condition are thermal insulation, we considered all internal walls of the furnace insulation( $q''=0$ ). The outlet diameter of the furnace such as the actual furnace is 1m and the temperature of the exhaust gases is considered 1027 °C. Input boundary conditions in numerical simulation, as shown in figure 3.



**Figure 3.** The overview of entrance boundary conditions in numerical simulation

## 4. Results

Temperature measurement is provided based on the temperature of central point of the load in table 2.

**Table 2.** Temperature measurement of central point of load

time (h: m: s)	$T_1$ (K) experimental temperature at point
10:03:33	317.5
10:05:33	319.9
10:07:33	318.3
10:09:33	318.8
10:11:33	319.2
10:13:33	319.7
10:15:33	320.1
10:17:33	320.4
10:19:33	320.8
10:21:33	321.2
10:23:33	321.5
10:25:33	321.8

10:27:33	322.2
10:29:33	322.4
10:31:33	322.7
10:33:33	322.8

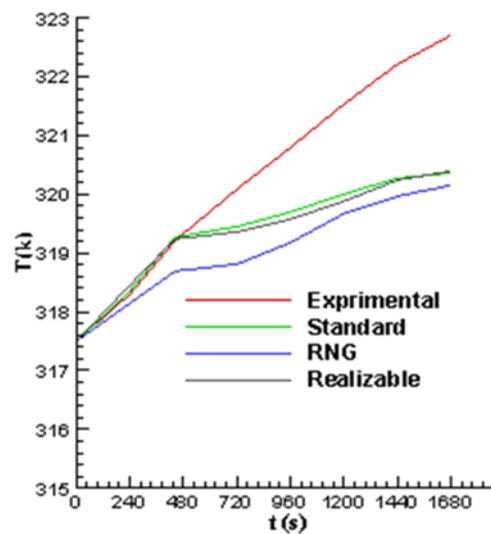
#### 4.1. Evaluation of turbulence models

Regard to experimental data, initial temperature load in numerical simulation was assumed set the temperature  $T_1$  (317.5 K).

In order to evaluate the good turbulence models in the numerical solution, we studied the two-equation turbulence models. The numerical data was presented accompanying with experimental data in table 3 and figure 4.

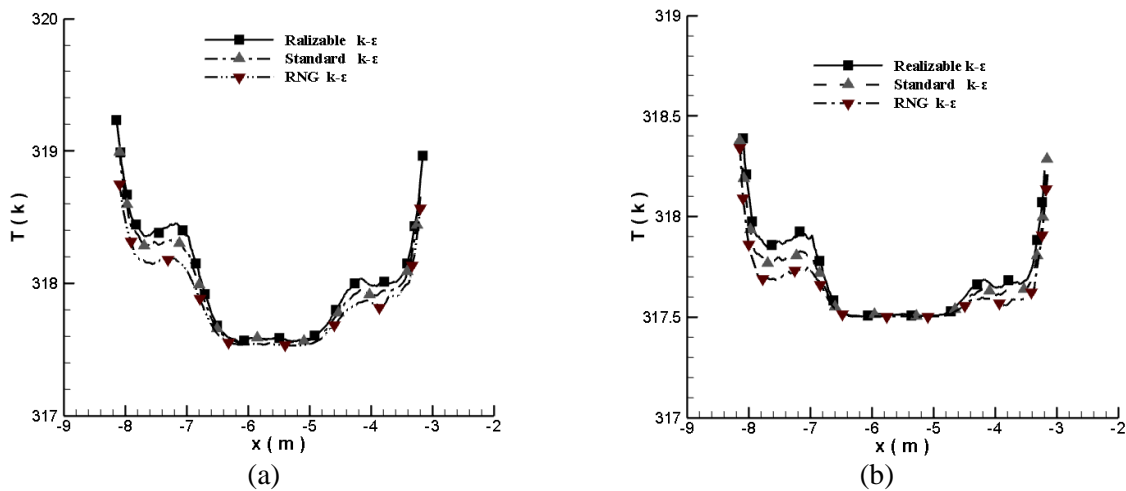
**Table 3.** Load numerical temperatures ( $T_1$ ) for three turbulence models comparison with experimental data

t(s)	experimental temperature (K)	numerical temperature Standard k- $\epsilon$ model (K)	numerical temperature RNG k- $\epsilon$ model (K)	numerical temperature Realizable k- $\epsilon$ model (K)
0	317.5	317.5	317.5	317.5
240	318.3	318.35	318.131	318.45
440	319.2	319.26	318.678	319.24
720	320.1	319.46	318.8	319.34
960	320.8	319.69	319.17	319.56
1200	321.5	319.98	319.66	319.88
1440	322.2	320.28	319.95	320.23
1680	322.7	320.36	320.136	320.4
1800	322.8	320.38	320.24	320.58



**Figure 4.** Numerical data of three turbulence models for ( $T_1$ ) in comparison with experimental data

The figure 4 shows the performance of the different turbulence models. Standard and Realizable  $k-\epsilon$  was almost the same in the numerical solution. In comparison to experimental data both of them illustrate the better performance than the RNG  $k-\epsilon$  model. As shown in figure 11, the distribution temperature along of load's central line at the time of  $t = 30$  Min and  $t = 15$  Min are shown in figure 5(a, b).



**Figure 5.** Load central line profile temperature (a) at the time  $t = 30$  Min (b) at the time  $t = 15$  Min

Temperature of load's that was predicted by Realizable  $k-\epsilon$ , is more than the other models in different times and closer to experimental data. So, it is found that the Realizable  $k-\epsilon$  turbulence model is a good candidate for investigation heat transfer of heat treatment furnace.

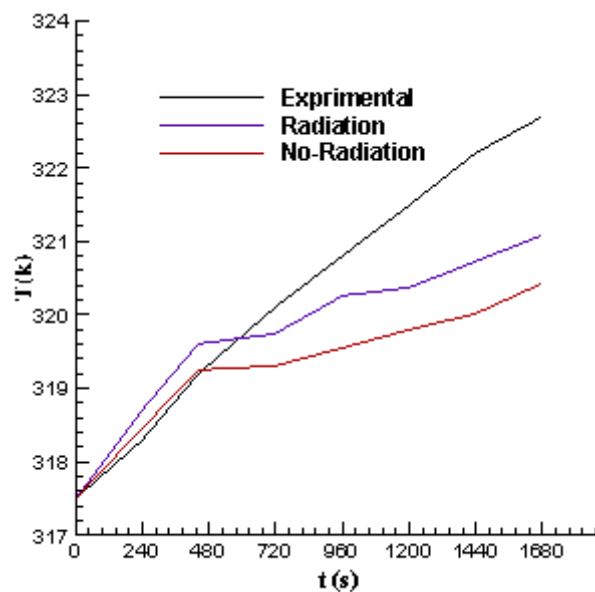
#### 4.2. The effect of radiation

The following Consideration is the evaluation of. Numerical results with regard to the Realizable  $k-\epsilon$  turbulence model and considering the radiation in calculations with experimental results have been presented in table 4 and figure 6.

**Table 4.** Target load numerical temperature ( $T_1$ ) for considering of radiation and without radiation

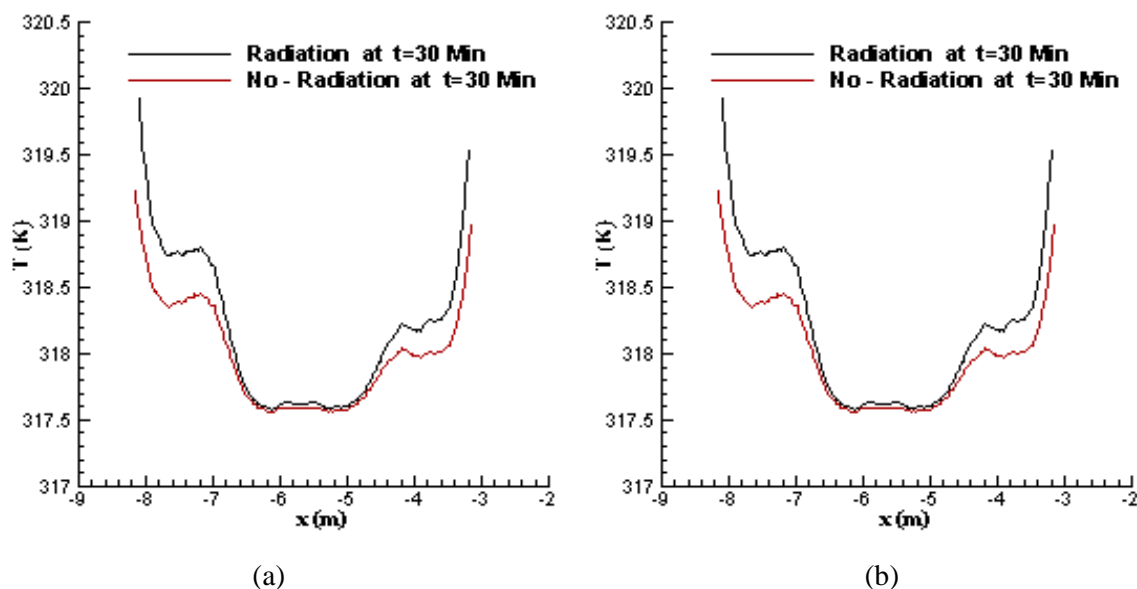
t(s)	experimental temperature $T_1$ (K)	numerical temperature without radiation $T_1$ (K)	numerical temperature with radiation $T_1$ (K)
0	317.5	317.5	317.5
240	318.3	318.45	318.71
440	319.2	319.24	319.6
720	320.1	319.308	319.75
960	320.8	319.56	320.27
1200	321.5	319.78	320.364
1440	322.2	320.13	320.7
1680	322.7	320.4	321.07
1800	322.8	320.58	321.25





**Figure 6.** Numerical temperature results considering the radiation compared with the experimental temperature

The figure 6 shows that the considering radiation in calculations improved the numerical prediction. The load's central line temperature distribution is shown in figure 7. And, it is seen that when the radiation is considered in calculations, more heat reaches to the inside load based on the time, and temperatures in its central line is getting higher compared to the state of no radiation.



**Figure 7.** Load's central line temperature distribution:  
(a) at the time  $t = 30$  Min (b) at the time  $t = 15$  Min

## 5. Conclusion

Three dimensional numerical analysis was performed to obtain the realistic study of the heat treatment furnaces concerning in Steel industries. First, the performance of three two-equation turbulence models accompanying with experimental data were examined. The results of this study showed that the



performance of Standard k- $\epsilon$  turbulence and Realizable k- $\epsilon$  models in the numerical solution were approximately similar and better than RNG k- $\epsilon$  turbulence model. As a conclusion, it was indicated that in Realizable k- $\epsilon$  model, the load's central line predicted temperature was more than the other two models in different times, and it is closer to the experimental data. Second, due to studying the radiation effect on numerical simulation, it was revealed that results were improved 33% regard to experimental data.

## Reference

- [1] Dossett J L and Boyer H E 2006 Fundamentals of the heat treating of steel practical heat treating book Second Edition ASM International 9-25.
- [2] Keramida E P, Liakos H H, Founti M A, Boudouvis A G and Markatos N C 2000 Radiative heat transfer in natural gas-fired furnaces *International Journal of Heat and Mass Transfer* volume 4 pp 1801-1809.
- [3] Keramida E P, Liakos H H, Founti M A, Boudouvis A G and Markatos N C 2000 The discrete transfer radiation model in a natural gas-fired furnace *International Journal for Numerical Methods in Fluids* volume 34 pp 449-462.
- [4] White M K and S. D. Probert 1991 Heat transfers in treatment furnace *Applied Energy* volume 38 pp 293-323.
- [5] P. Sompong, S. Witayangkurn, Simulation of natural convection in a complicated enclosure with two wavy vertical walls 2012 *Applied Mathematical Sciences*, volume 6 issue 57 pp. 2833 – 2842,
- [6] Lari K, Baneshi M, Gandjalikhan Nassab S A, Komiya A and Maruyama S 2011 Combined heat transfer of radiation and natural convection in a square cavity containing participating gases, *International Journal of Heat and Mass Transfer* volume 54 pp 5087–5099.
- [7] Kang J and Rong Y 2006 Modeling, and simulation of load heating in heat treatment furnaces, *Journal of Materials Processing Technology* volume 174 pp109–114.
- [8] Tagliafico L A and Senarega M 2004 A Simulation code batch heat treatments *International Journal of Thermal Sciences* volume 43 pp 509-517.
- [9] Anderson L and Hakansson M 2007 Simulation of energy balances in a heat treatment furnace with Matlab and Comsol Multiphasics, Department of Chemical Engineering, Lund Institute of Technology Lund, Sweden.
- [10] Kim M Y 2007 A heat transfer model for the analysis of transient heating of the slab in a direct-fired walking beam type reheating furnace *International Journal of Heat and Mass Transfer* volume 50 issue19-20 pp 3740-3748.
- [11] Khoukit T and Tangthieng C 2014 A numerical investigation of the temperature uniformity of a Billet due to Thermal Radiation in a Reheating Furnace *Engineering Journal* volume 20 issue 1 pp 35-46.
- [12] Dubey S K and Srinivasan P 2013 Three dimensional transient explicit finite difference heat transfer modeling of billet transport *Thermal & Environmental Engineering* volume 6 issue2 pp 95-100.
- [13] Jang J Y, Lee Y W and Wang C H 2014 3-D transient heat transfer analysis of slab heating characteristics in a reheating furnace in hot strip mill *International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering* volume 19 issue10 pp 1851-1855.
- [14] Jang H J, LEE D E, KIM C and Kim M Y 2008 Prediction of furnace heat transfer and its influence on the steel slab heating skid mark formation in a reheating furnace *ISIJ International* volume 48 issue 10 pp 1325-1330.
- [15] Lee G W and Kim M Y 2014 On the thermal behaviour of the slab in a reheating furnace with radiation *International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering* volume 8 issue5 pp 922-927.

- [16] Wu J, You H, Radhakrishnan P, Wei W and Ming R Y 2004 Modeling and simulation of heat transfer in loaded continuous heat treatment furnace *Transactions of Materials and heat treatment proceedings of the IFHTSE congress* volume 25 pp 3740–3748.
- [17] Minea A 2010 Numerical simulation and experimental validation of heat transfer enhancement on a loaded heat treatment furnace *Journal of Engineering Thermophysics* volume 19 issue 3 pp 1-8.
- [18] Chapman K S, Ramadhyani S and Viskanta R 1990 Modelling and parametric studies of heat transfer in a direct-fired batch reheating furnace *Heat Treating* volume 8 pp137-146.
- [19] Kanury A M 1977 Introduction to combustion phenomena first edition New York.
- [20] Fluent 6.3, User's Guide, 2006.