journal homepage: www.elsevier.com/locate/jmatprotec

Thermal analysis of sponge iron preheating using waste energy of EAF

Ebrahim Hajidavalloo, Ali Alagheband*

Mechanical Engineering Department, Shahid Chamran University, Ahvaz, Iran

ARTICLE INFO

Article history:
Received 1 April 2007
Received in revised form
22 December 2007
Accepted 31 December 2007

Keywords:
Sponge iron
Fixed bed
Electric energy saving
Preheating
Flue gas

ABSTRACT

Energy consumption and production capacity are two major concerns in the steel making industries which are using electric arc furnace (EAF). To improve the performance of EAF, a new initiative technique has been introduced in which sponge iron particles are preheated before entering the furnace. A heat exchanger is used to transfer waste energy from EAF flue gas to a neutral gas like nitrogen, which in turn preheats the sponge iron particles in the fixed bed. The method has several desirable advantages including electric energy saving, increasing the productivity and reduction in electrode and refractory consumption. In order to estimate the extent of energy saving and productivity increase, the preheating process was simulated in the bed. The thermal characteristics of the fixed bed were predicted by a numerical solution of differential equations for granular sponge iron and heating gas. The temperature of sponge iron particles and heating gas were also predicted in different layers of the bed and at different times. Based on the simulation results it is found that the energy consumption in the EAF can be reduced up to 14% and productivity can be increased up to 13%.

1. Introduction

The iron and steel industry is the largest industrial energy consumer. According to Camdali et al. (2003), approximately 12% of the world energy production is used in the iron and steel section. Bisio et al. (2000) reported that after the employee costs, energy costs (about 30% of the total cost) represent the second highest cost element in integrated steel works. The share of the electric arc furnace (EAF) technology in the iron and steel industry is increasing rapidly and is estimated for at least 50% of the total steel production in 2010 based on the prediction of Raja et al. (2005). Future growth in EAF steelmaking depends on continued improvements in energy use, operating costs, and furnace productivity. It is a well-known fact that over 20% of the energy generated in EAF is left in the form of off-take gases. Melting of iron by EAF is a very energy consuming process in which temperature of sponge iron particles is raised from ambient temperature up to 1500 °C. Since electrical energy which is the most expensive form of energy used in EAF, lowering the energy consumption is a major concern in these industries.

Various technologies have been developed so far to reduce electrical energy in steel making industries. One of the important technologies is hot charging of sponge iron particles which was developed by Midrex Company and discussed by Montague and Hausler (1999). In this technology hot sponge iron (up to 700 °C) is charged into the furnace by taking advantage of gravity as driving force which resulted in considerable saving in power and electrode consumption as well as higher EAF productivity. Further modification in the hot charging technique was discussed by Baily (2001).

* *Corresponding author*. Tel.: +98 611 3363228; fax: +98 611 3369684.
E-mail address: hajidae_1999@yahoo.com (E. Hajidavalloo).
0924-0136/$ – see front matter
doi:10.1016/j.jmatprotec.2007.12.140

Nomenclature

A_b	bed cross-section area (m^2)
A_p	particle surface area (m^2)
A_s	bed lateral area (m^2)
C_p	specific heat of particle ($kJ\,kg^{-1}\,K^{-1}$)
C_i	specific heat of inlet gas ($kJ\,kg^{-1}\,K^{-1}$)
d_b	bed diameter (m)
d_p	particle diameter (m)
E	energy (kJ)
h_p	heat transfer coefficient between particle bed and gas ($W\,m^{-2}\,K^{-1}$)
h_s	heat transfer coefficient between inlet gas and surface ($W\,m^{-2}\,K^{-1}$)
ΔH	sponge iron specific heat of fusion ($kJ\,kg^{-1}$)
k_p	thermal conductivity of particle ($W\,m^{-1}\,K^{-1}$)
L_c	characteristic length of particle (m)
Re	Reynolds number ($=d_p u_i \rho_i/\mu_i$)
Sc	Schmidt number ($=\mu_i/\rho_i d_p$)
T_i	inlet temperature of gas (K)
T_p	particle temperature (K)
T_s	bed surface temperature (K)
u_i	inlet velocity of gas ($m\,s^{-1}$)
V_p	particle volume (m^{-3})
Greek letters	
α	thermal diffusivity ($m^2\,s^{-1}$)
ε	dimensionless volume fraction
ρ	density ($kg\,m^{-3}$)
σ	radiation constant ($w\,m^{-2}\,K^{-4}$)
Subscripts	
b	bed
i	inlet gas
p	particle

Another technology for reducing energy consumption is preheating irons by flue gas. Preheating scheme could be divided in two categories, either scrap iron preheating or sponge iron preheating. Many elaborate processes have been developed so far to use flue gas energy for scrap iron preheating including BBS Bursa, Fuchs shaft furnace, and CONSTEEL® scrap preheater. Schmitt (1997) reported that the CONSTEEL® technique can reduce electric consumption up to 18%, and increase production up to 17%.

Although there have been many technologies for scrap iron preheating, sponge iron preheating has not been considered in steel making industries yet. In this paper sponge iron preheating scheme by using flue gas is introduced. Since sponge iron particles are stored in silo before they enter the furnace, there is enough time for preheating.

In order to find out how much energy can be transferred to the sponge iron particles, the heating process in the silo should be simulated. Sponge iron particles in the silo can be considered as a fixed bed. Fixed bed has been used in many industries for heating and drying of particles. It is considered to be convenient equipment for heat storage effort. Due to the large surface-to-volume ratio, the thermal response of these units is relatively fast as compared to other developed energy carrier devices. Costa and Figueiredo (1990) applied mixing cells model to predict the behavior of packed bed dryers. Achenbach (1995) presented correlations for prediction of convective heat transfer coefficient, pressure drop, effective conductivity, and wall heat transfer in the fixed bed. Amiri and Vafai (1998) investigated the temporal energy transport of incompressible flows through fixed bed. Hessari et al. (2004) studied the behavior of packed bed of rock material and simulated the heating process inside the bed and obtained the profiles of air and rock bed temperatures with respect to the time and length of the bed.

Although the thermal behaviors of different particles have been studied in the fixed bed with different variations and extensions, there is no information available on the sponge iron particles behavior in the fixed bed. In this paper, first, the concept of sponge iron preheating in the EAF industry is introduced and then, the thermal behavior of sponge iron particles in the fixed bed are simulated in order to find out the extent of energy saving and productivity increase.

2. Proposed design

In the conventional design of EAF, the hot flue gas of EAF passes through the water-cooled duct and the radiant cooler (to reduce the temperature) and finally exhausts to the atmosphere by using an ID fan. The flue gas is a good source of energy because it has high mass flow rate and high temperature. For example, for a typical EAF, the mass flow rate and temperature of gas are about 1035 kg/min and 1100 °C, respectively, which contain thermal capacity of about 18 MW. This huge source of thermal power could be used for sponge irons preheating which in turn reduce electrical energy consumption in the furnace.

Another important aspect of the sponge irons preheating is decreasing the melting time of sponge iron and therefore increasing the productivity of the furnace. Usually tap-to-tap melting time of iron takes about 120 min. If by preheating the sponge irons, tap-to-tap time is decreased about 10%, then the plant production will be increased about 10%. The increase in production will have tremendous financial impact for the plant.

The furnace flue gas cannot directly be used to preheat the sponge iron particles because of re-oxidation of the particles. Therefore, an intermediate gas should be used for preheating process. Nitrogen is a very good candidate for this purpose because it does not react with sponge iron particles and also it is available enough as by-product of other processes in the steel making plants.

In this design, nitrogen picks up heat from the hot flue gas through a heat exchanger which can be located inside the exit duct of the furnace and then the hot nitrogen enters the silo to preheat the sponge iron particles. Exit nitrogen could be circulated into the cycle in order to save nitrogen consumption. A cyclone is used in the nitrogen cycle to separate any dust which might be carried out with nitrogen. Fig. 1 shows the schematics of the design for an actual EAF. In order to find out the estimate of energy saving and productivity increase, it is required to simulate the processes in the silo and the furnace.

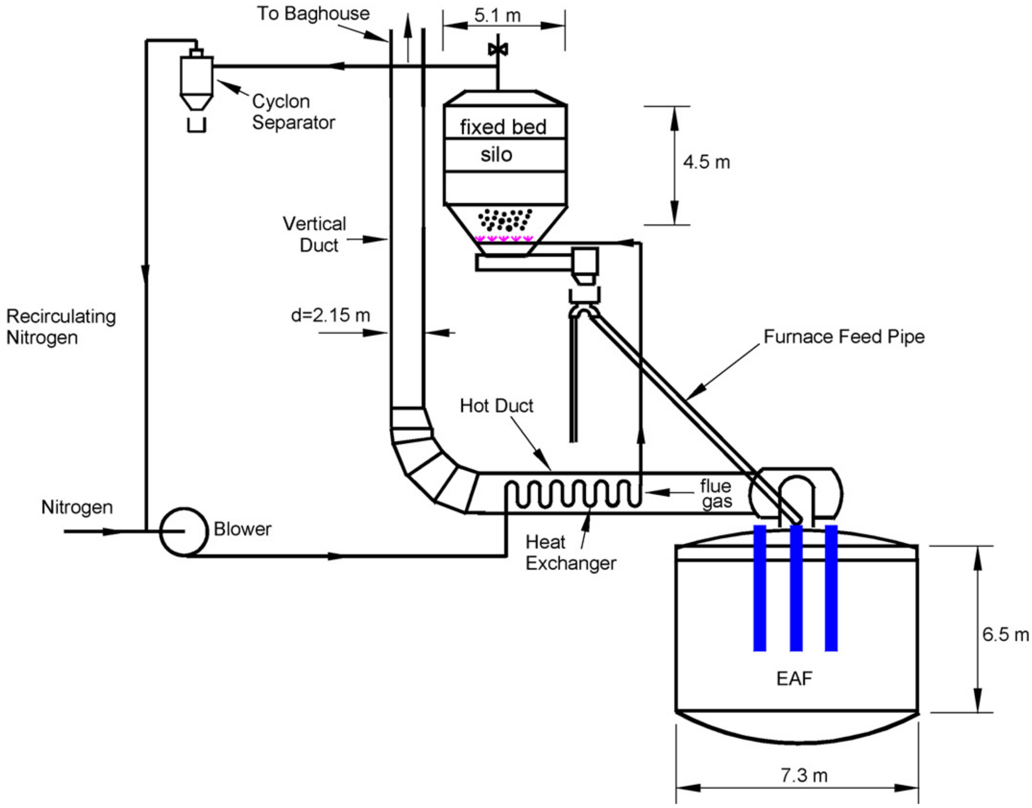

Fig. 1 – Layout of the design for preheating the sponge iron in fixed bed by using flue gas.

In the simulation, validated models in the literature were used as discussed by Costa and Figueiredo (1990) and Palancz (1985).

3. Modeling the process

Sponge iron particles can be considered as spherical shape with average diameter of 1 cm. The bed dimension is shown in Fig. 1 and the thermal properties of sponge iron are as

$d_p = 1\,\mathrm{cm}$

$\rho_p = 4000\,\mathrm{kg\,m^{-3}}$

$C_p = 0.460\,\mathrm{kJ\,kg^{-1}\,K^{-1}}$

$\Delta H = 280\,\mathrm{kJ\,kg^{-1}}$

$k_p = 5.01\,\mathrm{W\,m^{-1}\,K^{-1}}$

$\varepsilon_p = 0.5$

In order to understand the thermal characteristics of the bed, a mathematical model was developed. The following simplifying assumptions were used in order to derive the governing equations.

- The air flow is one-dimensional.
- Conduction between bed particles is negligible.
- Bed walls are adiabatic.
- Radiation heat transfer in the bed is negligible.

For modeling gas and particles behavior, it is required to divide the bed into a number of one-dimensional control volumes as shown in Fig. 2. For each control volume, the energy equation in differential form can be developed for nitrogen and particles.

The energy balance for the gas in the control volume can be written as

$$\dot{E}_{\mathrm{in}} - \dot{E}_{\mathrm{out}} + \dot{E}_{\mathrm{gen}}\,\mathrm{d}V = \frac{\partial E}{\partial t} \tag{1}$$

where

$$\dot{E}_{\mathrm{in}} = \rho_i C_i \varepsilon_i A_b u_i T_i \tag{2}$$

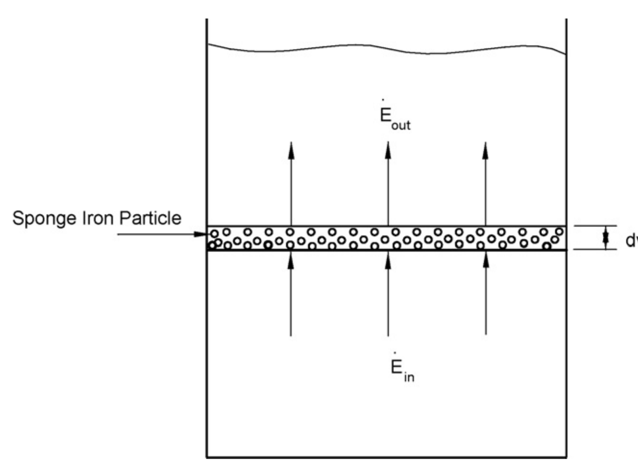

Fig. 2 – One-dimensional control volume for energy balance.

$$\dot{E}_{out} = \rho_i C_i \varepsilon_i A_b u_i T_i + \frac{\partial(\rho_i C_i \varepsilon_i A_b u_i T_i)}{\partial y} dy \tag{3}$$

The heat generation term has two parts, one for the convection between gas and solid particles and the other for the convection between gas and surface of the bed wall which can be written as

$$\dot{E}_{gen} = \dot{E}_{g,particle} + \dot{E}_{g,surface} \tag{4}$$

$$\dot{E}_{g,particle} = h_p(T_p - T_i)\frac{A_p}{A_b\,dy} \tag{5}$$

$$\dot{E}_{g,surface} = h_s(T_s - T_i)\frac{A_s}{A_b\,dy} \tag{6}$$

After substituting the above equations and simplifying them, as reported by Hajidavalloo and Hamdullahpur (2000), Eq. (1) can be re-written as

$$\frac{\partial}{\partial t}(\rho_i C_i \varepsilon_i T_i) + \frac{\partial}{\partial y}(\rho_i C_i \varepsilon_i U_i T_i) = h_p(T_p - T_i)\frac{6\varepsilon_p}{d_p} + h_s(T_s - T_i)\frac{(1-\varepsilon_p)}{d_b} \tag{7}$$

The bed voidage and gas velocity are constants during the process but the physical characteristics like ρ_i and C_i depend on the local temperature at each layer.

The bed wall is considered adiabatic; therefore, the heat transfer to the wall can be neglected. Based on these assumptions, Eq. (7) can be written as

$$\frac{\partial}{\partial t}(\rho_i C_i T_i) + U_i \frac{\partial}{\partial y}(\rho_i C_i T_i) = \frac{6h_p(T_p - T_i)}{\varepsilon_i}\frac{\varepsilon_p}{d_p} \tag{8}$$

4. Modeling the energy equation for sponge iron particles

Two models can be used for predicting the sponge iron behavior inside the bed. The first model is the lumped capacitance and the second model is the diffusion model. In order to find out which model is suitable, Biot number should be calculated as

$$Bi = \frac{h_p L_c}{k_p} \tag{9}$$

where L_c equals to $r_o/3$ and h_p is obtained from Ranz (1952) equation as

$$h_p = \frac{k_p}{d_p}(2 + 1.8Re_p^{1/2}Sc^{1/3}) \tag{10}$$

The Biot number of particle is equal to 0.04 which is less than 0.1; therefore, the lumped capacitance model can be used in the calculation with negligible error. The energy equation for the sponge iron particle takes the form

$$h_p A_p(T_i - T_p) = \rho_p C_p V_p \frac{\partial T_p}{\partial t} \tag{11}$$

5. Method of solution

Eqs. (8) and (11) should be solved simultaneously in order to obtain the variation of gas and solid temperature in terms of bed height and time. The first equation, which is for the gas flow, is hyperbolic partial differential equation and the second one, which is for the sponge iron particles, is simple differential equation. Initial and boundary condition are as

$$T_i(y, 0) = T_{io} \tag{12}$$

$$T_p(y, 0) = T_{po} \tag{13}$$

$$T_i(0, t) = T_{ih} \tag{14}$$

where T_{io}, T_{po}, and T_{ih} are known as constants. To reach more accurate solution, the flow field in the bed is divided into a finite number of control volumes and an upwind implicit scheme is employed to discritize the equations in space and time domain. The solution procedure is started by solving the set of equations for the first control volume which is at the bottom of the bed, and the gas and the particles temperature are evaluated inside the control volume. Then, the solution marches into the next control volume and all the properties are calculated again for the condition of this control volume. The marching procedure continues until it reaches the last control volume.

6. Results

In order to investigate the effect of various parameters on the preheating process, simulation was carried out on an existing sponge iron silo located at Khouzestan Steel Company in Ahvaz, Iran. The bed has rectangular cross-section (2.5 m × 5.1 m) with 4.5 m height containing about 75 tonnes of sponge iron particles.

Fig. 3 shows the variations of gas temperature with time at different heights of the bed. It can be seen from the figure that the gas temperature increases more rapidly at the bottom of the bed compared to the upper section. This means that at the bottom of the bed gas temperature is close to the inlet temperature most of the time.

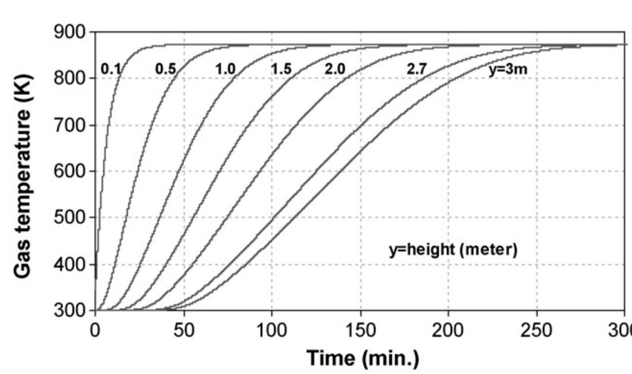

Fig. 3 – Variation of gas temperature with time at different heights (T_{in} = 873 K).

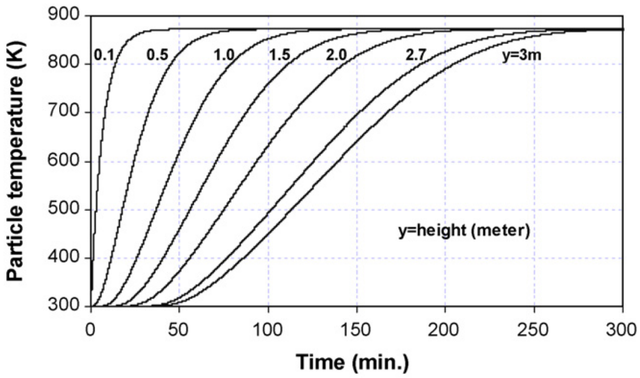

Fig. 4 – Variation of particle temperature with time at different heights (T_{in} = 873 K).

Fig. 4 shows the variations of particle temperature with time at different layers of the bed. The temperature variations of the particles are very similar to the gas temperature variations. Initially the difference between temperature of gas and sponge iron particles is important but as time proceeds the difference becomes negligible which indicates that the gas and particles reach thermal equilibrium very fast. This is in agreement with other finding given in the literature like Hessari et al. (2004) and Holman (2002).

Fig. 5 shows the temperature distribution of sponge iron particles at different times inside the bed. It can be seen that at initial stage of the process only the temperature of the bottom layers increases and the temperature of upper layer does not change so much but as time proceeds the temperature of the upper layers also increases.

Figs. 6 and 7 show the effect of mass flow rate of gas on the particles temperature inside the bed at different times. It can be seen that mass flow rate has considerable effect on the particle temperature profile and by increasing it the temperature rise inside the bed increases more rapidly.

Fig. 8 shows the total energy saved by particles inside the bed at two different gas inlet temperatures. The total energy is the summation of all particles energy at different layers of the bed. The figure shows how much energy is absorbed in the bed at any time. It can be seen that at the initial stage energy absorption increases rapidly but as time proceeds, energy absorption approaches a constant value. The time at which the total energy does not change is an indication that all particles have reached thermal equilibrium with gas temperature and no more energy absorption takes place. Therefore, by using this graph the duration time necessary to preheat the sponge iron particles up to the inlet gas temperature can be calculated.

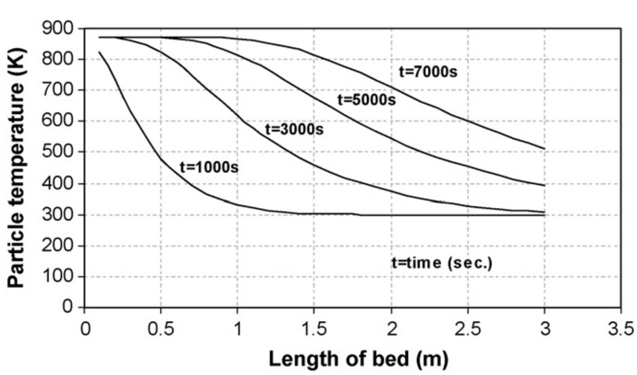

Fig. 5 – Temperature distribution of particles in bed at different times.

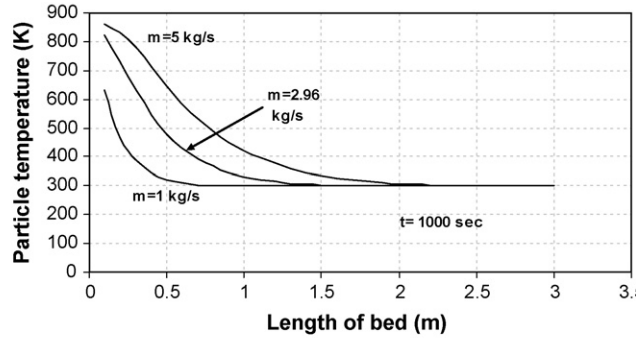

Fig. 6 – Effect of mass flow rate of gas on the particles temperature inside the bed (T = 873 K, t = 1000 s).

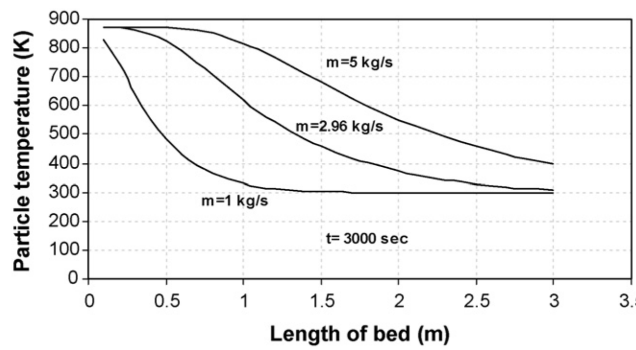

Fig. 7 – Effect of mass flow rate of gas on the particles temperature inside the bed (T = 873 K, t = 3000 s).

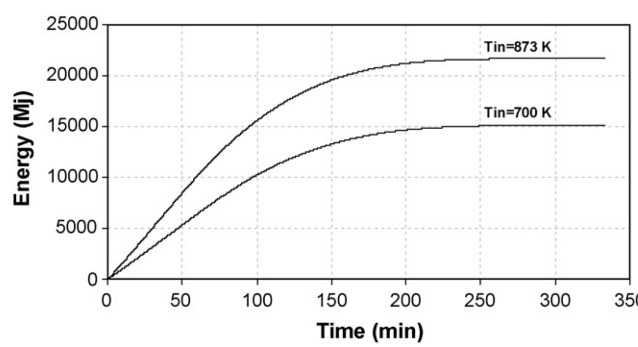

Fig. 8 – Energy received by particles at two inlet temperatures of gas.

7. Discussion

7.1. Energy saving

Based on the results of simulation, the amount of energy saving in the plant can be calculated. If the tap-to-tap time of the furnace is assumed to be about 120 min (which is usual in steelmaking industry), then the average temperature increase in the bed could be easily calculated from Fig. 8 and energy balance in the bed. For the case under the study, the energy balance shows the average temperature increase is about 480 °C if the inlet gas temperature is 600 °C. As a rule of thumb, power consumption can be reduced to about 20 kWh/tonnes of liquid steel for each 100 °C increase in the charge temperature. Therefore, for this plant, total power saving would be about 96 kWh/tonnes of liquid steel. A comparison of this power saving with the present power consumption of the plant (677 kWh/tonnes of liquid steel) shows there would be 14% power reduction.

More power saving will be attained if inlet gas temperature increases further. This increase can be fulfilled by different methods like increasing the mass flow rate of the gas in the cycle.

7.2. *Productivity increase*

The other major benefit of sponge iron preheating scheme is increasing the production rate of the furnace due to shorter tap-to-tap time. There are different data to address the amount of time reduction in the melting process for any increase in the charge temperature because it is highly plant dependent and many other parameters should be considered as reported by Baily (2001). If, based on the simple energy analysis, it is assumed for each 100 °C increase in the charge temperature, tap-to-tap time can be reduced to about 3 min, then for the plant, tap-to-tap reduction time would be about 15 min which could be about 13% reduction in tap-to-tap time. In other words the production rate can be increased up to 13%. The production rate can be increased more if inlet gas temperature is increased.

Other advantages of using this method are saving in electrode and refractory consumption, decreasing moisture in EAF feed and reducing environmental emissions. The different advantages of preheating technique have considerable financial benefits for the plant which can be the subject of some further researches.

8. Conclusion

There is huge amount of energy and exergy wasted in EAF industry which can be reused by application of proper scheme. Preheating the sponge iron particles is one of the feasible schemes which could be applied in order to decrease energy consumption and increase productivity. In this scheme, flue gas energy is transferred to a neutral gas through a heat exchanger and then the hot gas is used to preheat the sponge iron particles held in the silo. Simulation of preheating process shows that using this technique electrical energy can be saved up to 14% and furnace productivity can be increased up to 13%. There is good potential to further increase in saving by increasing the inlet gas temperature.

Acknowledgement

The authors would like to thank the Research and Development Department of Khuzestan Steel Company for the financial support of this research.

REFERENCES

Achenbach, E., 1995. Heat and flow Characteristics of packed beds. Exp. Therm. Fluid Sci. 10, 17–27.
Amiri, A., Vafai, K., 1998. Transient analysis of incompressible flow through a packed bed. Int. J. Heat Mass Transf. 41, 4259–4279.
Baily, R., 2001. Benefits of hot DRI charge to the EAF, Direct from Midrex, 2nd Quarter, pp. 7–8.
Bisio, G., Rubatto, G., Martini, R., 2000. Heat transfer, energy saving and pollution control in UHP electric-arc furnaces. Energy 25, 1047–1066.
Camdali, U., Tunc, M., Karakas, A., 2003. Second law analysis of thermodynamics in the electric arc furnace at a steel producing company. Energy Convers. Manage. 44, 961–973.
Costa, V.A.F., Figueiredo, A.R.A., 1990. The mixing cells model applied to a fixed bed dryer. Can. J. Chem. Eng. 68, 876–880.
Hajidavalloo, E., Hamdullahpur, F., 2000. Thermal analysis of fluidized bed drying process for crops. Part I: Mathematical modeling. Int. J. Energy Res. 24, 791–807.
Hessari, F.A., Parsa, S., Khashechi, K., 2004. Behavior of packed bed thermal storage. Int. J. Eng. Trans. A: Basics 16, 181–192.
Holman, J.P., 2002. Heat Transfer, ninth ed. McGraw-Hill, New York, pp. 550–553.
Montague, C.S., Hausler, W.D., 1999. Hotlink, hot charging DRI for lower cost and higher productivity. In: Iron & Steel Society's 57th Electric Furnace Conference, Pittsburgh, USA, pp. 3–7.
Palancz, B., 1985. Modeling and simulation of heat and mass transfer in a packed bed of solid particles having high diffusion resistance. Comput. Chem. Eng. 9, 567–581.
Raja, B.V.R., Pal, N., Talwar, P.L., Jayaswal, N.P., 2005. Technologies for cost reduction in EAFs. Steelworld (April), 1–4.
Ranz, E., 1952. Fixation and transfer coefficients for single particles and packed bed. Chem. Eng. Prog. 48, 1045–1059.
Schmitt, J., 1997. Electric arc furnace scrap preheating. Electric Power Research Institute Inc. Technical Document, TechCommentary/TC-107874.