

Chakravarty, Koushik; Kumar, Sunil

Article

Increase in energy efficiency of a steel billet reheating furnace by heat balance study and process improvement

Energy Reports

Provided in Cooperation with:

Elsevier

Suggested Citation: Chakravarty, Koushik; Kumar, Sunil (2020) : Increase in energy efficiency of a steel billet reheating furnace by heat balance study and process improvement, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 6, pp. 343-349, <https://doi.org/10.1016/j.egy.2020.01.014>

This Version is available at:

<https://hdl.handle.net/10419/244037>

Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Terms of use:

Documents in EconStor may be saved and copied for your personal and scholarly purposes.

You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.



<https://creativecommons.org/licenses/by-nc-nd/4.0/>



Research paper

Increase in energy efficiency of a steel billet reheating furnace by heat balance study and process improvement



Koushik Chakravarty^{a,*}, Sunil Kumar^b

^a Tata Steel, Jamshedpur-831001, India

^b CSIR-National Metallurgical Laboratory, Jamshedpur-831001, India

ARTICLE INFO

Article history:

Received 30 July 2019

Received in revised form 28 January 2020

Accepted 30 January 2020

Available online xxxx

Keywords:

Heat balance
Energy efficiency
Reheating furnace
Fuel consumption
Thermocouple
Thermography

ABSTRACT

Steel is the inevitable material for the infrastructure and has the strategic importance for the growth of the country. Iron and steel making industry is one of the most energy-intensive industries, with 5% of the world's total energy consumption. Therefore, it is required to develop suitable and efficient energy management during various processing in steel plants. Both academic and industrial research is going on worldwide to increase the energy efficiency for reducing the energy cost imparted due to application of reheating furnaces in various metallurgical process. Reheating furnaces are widely used in the Iron and Steel Industry to reheat the semi-finished products like slabs or billets to the rolling temperature at 1250 °C. Reheating furnace is one of the major energy consuming equipment for rolling mills. It is also important to optimize the fuel consumption in this reheating process to avoid any overheating of the steel material which may result in the poor quality of the final product. The aim of this investigation is to conduct an analysis to explore possibilities for the improvement in the energy efficiency of an operating natural gas fired reheating furnace. Some important efficiency improvement measurements were conducted and the fuel efficiency improved by 21% along with the productivity increased by 11%. As a result of these investigations, some energy saving opportunities were ascertained. These measures culminate in the overall projected fiscal savings of INR 264 million/year. Our study not only provides efficient solutions to steel industry for proper energy utilization, but also offers ways for the self-innovation of other academic and laboratory scale research activity.

© 2020 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

1. Introduction

Reheating furnace is used to reheat materials for thermo-mechanical processing at various academic laboratories, pilot plants and large scale industry. Therefore, reheating furnaces must be designed and operated to achieve maximum thermal efficiency along with desired production rate, acceptable product quality, environment friendly output and so forth (An et al., 2018; Arink and Hassan, 2017; Charles and Cang, 2010; Hosseini et al., 2019; Karali et al., 2016; Palacios et al., 2019). In a large scale steel industry, reheating furnace is one of the most intensive energy consumer (Demin et al., 2018a,b; Enes et al., 2014; Ghanbari et al., 2012; Neumann et al., 2018; Han et al., 2007). In these reheating furnaces, the thermal efficiency plays an important role in reducing the energy cost and improving the product quality (Thakur et al., 2015; Hasanbeigi et al., 2014). In literature, an energy conservation based model has been used to determine various losses of energy in the process to increase the energy efficiency

(Ghanbari et al., 2012; Reyes and Luyben, 2000; Levenspiel, 1999). In this scope, the plant performance under operating conditions, temperature, pressure, velocity, and combustion gas measurement required to maintain without efficiency and thermal losses (Hasanbeigi et al., 2014; Juanicó and González, 2008; Kangvanskol and Tangthieng, 2014; Kaya et al., 2013a,b; Koymatcik et al., 2018; Levenspiel, 1999; Lv et al., 2019; Paulrud and Nilsson, 2001; Petchers, 2003; Reyes and Luyben, 2000; Steinboeck et al., 2010; Zhang et al., 2019; Zhao et al., 2019). Chen et al. (2005) have reported that the energy consumption and performance of reheating furnaces with energy efficiency (80.1%) calculated by both numerical predictions and practical measurements. Minxing et al. (2011) evaluated the energy efficiency of a steel factory and analyzed the feasibility of waste heat recovery in their study that was realized in Manitoba, Canada. Although there have been many good results achieved in studies on energy efficiency of the conventional industrial reheating furnace, the recommendations that made in these studies were not applied in most applications in a holistic manner with tangible techno-economic benefits. In our previous investigation (Chakravarty, 2016; Chakravarty et al., 2013), we have reduced losses or rejections in the process, which

* Corresponding author.

E-mail address: kaushik.chakravarty@tatasteel.com (K. Chakravarty).

Table 1
The burner details of the SCSC reheating furnace.

Zones	Type	No.	Maximum air flow (N m ³ /h)	Maximum fuel flow (N m ³ /h)
Preheating zone	BLF-G8	6	4138 × 6 = 24 828	396 × 6 = 2376
Heating zone	BLF-G6	6	3065 × 6 = 18 390	294 × 6 = 1764
Soaking zone	BLF-G3	10	943 × 10 = 9430	90 × 10 = 900

helps us in reducing the proportionate energy consumption and improving the product yield. Despite of above investigations, none of the studies reported earlier have been conducted on the walking hearth type natural gas fired reheating furnace. Therefore, it is required to identify the factors affecting the fuel consumption in a slab reheating furnace and possible actions are taken on each factor to reduce the fuel consumption.

In the present investigation, we have reported detail analysis related to heat-mass transfer and thermal efficiency calculation of Wire Rod mill at SCSC (Siam Construction, Steel Company; located in Rayong province, Thailand). It has a Walking Hearth type Natural Gas fired reheating furnace which processes billets of 150 mm² and 12 m long to a temperature of 1180 °C for rolling. The total capacity of plant is 100 TPH (Tons per hour). The furnace is divided into three zones viz. Preheating zone (PHZ –1), Heating zone (HZ –2) and Soaking zone (SZ –3&4). Soaking zone is further divided into two parts having five burners each left & right. The natural gas with the calorific value of 36 006 kJ/N m³ is used as fuel here. The burner details of the SCSC reheating furnace are given in Table 1.

In order to increase energy efficiency, there have been successful studies carried out and some important solutions were recommended. Thereby, these achieved solutions were applied and put into the practice with tangible techno-economic benefits. Our results will be enhance the understanding to build energy efficient setups in both academic laboratory and large scale steel making plants. Our views and processing steps for maximizing energy efficiency also enhance productivity, reduces space and apparatus required for storage, and ensures a competitiveness with respect to the pricing. In future, business strategies, goals, expansion and investment plans will be dependent on the energy consumption and efficiency projects.

2. Methodology

The heating operation in the reheating furnaces is associated with combustion of fuel gas and preheated air (Chen et al., 2005; Minxing et al., 2011; Chakravarty, 2016; Chakravarty et al., 2013; Trinks et al., 2004). The heat that goes into an industrial process typically leaves the process as, flue gas, wall losses, opening losses, heat to load (useful heat) and cooling system losses (water is used as coolant in the skids/rolls/doors usually). Because the input energy must match the sum of all of the output energy streams – useful or wasteful – reducing any of the losses described above will reduce the input energy requirements according to specific relationships of temperature, mass-flow, heat capacities (air, combustion products, feedstock, fixtures) and heat transfer (Han et al., 2010; Jenkins and Mullinger, 2011; Rachel et al., 2013; Steinboeck et al., 2010). Operational practices are also important for the energy efficiency. To illustrate the opportunities for energy savings, the schematic shown in Fig. 1 may be considered for analytical study.

The generic calculation of thermal energy analysis is based on the heating value of the fuel, the quantity of heat leaving the process in the flue gases (Petchers, 2003), and the amount of heat that can be put back into the process by preheating

the combustion air. This general relationship is described in the equation below:

$$\%Saving = \left\{ 1 - \frac{\text{Heating value of fuel} - \text{Heat in flue gases}}{\text{Heating value of fuel} + \text{Heat in combustion air} - \text{heat in flue gases}} \right\} \times 100 \quad (1)$$

To calculate a numerical result of this general equation (1), one needs to know both the composition of the fuel and also the amount of excess air that is in the flue gas (Paulrud and Nilsson, 2001). Of course, the flue gas temperature and the desired combustion air preheat must also be input. The efficiency of the furnace can be computed by measuring the amount of fuel consumed per unit weight of material produced from the furnace. The quantity of heat to be imparted to the stock can be found from the following formulae.

$$Q = mC_p (T_2 - T_1) \quad (2)$$

where, Q is the quantity of heat in kJ, m is the mass of the material in kg, C_p is the mean specific heat, T₁ and T₂ are the initial and final desired temperature of the charge before it enters the furnace.

The thermal efficiency (TE) of the furnace (Juanicó and González, 2008) is calculated as given by Eq. (3).

$$TE = \frac{\text{Heat in the stock}}{\text{Heat in the consumed fuel}} \quad (3)$$

The efficient utilization of fuel in a reheating furnace is primarily determined by the following three factors: Complete combustion of the fuel in the furnace, deep cooling of the combustion products during their passage through heating surfaces and minimization of heat losses to the environment.

In the current study, a simple heat balance approach has been developed with the following assumptions: (a) the system is in steady state (b) solid charge materials enter the furnace at average charging temperatures of 640 °C (measured by the online pyrometer) (c) an average of 80% hot charging is considered. The total heat energy of the system involves the sensible heat of the input and output streams, the heat of the major chemical reactions is those taking place in the furnace, and the heat loss. Accordingly, under steady state condition, the generic heat balance equation for the furnace (Reyes and Luyben, 2000) can be written as given in Eq. (4).

$$\{\text{Heat in}\} + \{\text{Net heat generated by combustion reaction}\} = \{\text{Heat out}\} + \{\text{Heat loss}\} \quad (4)$$

The term “Heat in” has contributed from two major sources as chemical heat of fuel combustion, heat of exothermic reaction and sensible heats of preheated air, respectively. In the present calculation, the term “Heat out” consists of heat content of all the items which are leaving the furnace. It includes sensible heat to billets, waste gases, heat loss through walls, radiant heat through the doors and cooling water losses. Heat is lost through the furnace walls during production. These losses are caused by the conduction of heat through the walls, roof, and floor of the heating device (Hasanbeigi et al., 2014). The following measurements have been undertaken for formulating the energy balance in natural gas fired reheating furnaces.

1. Weight of stock/Number of billets heated,
2. Volume of fuel and air consumed,
3. Temperature of furnace walls, roof etc.
4. Flue gas temperature before and after the recuperator,
5. Charging and discharging temperature of the billets.

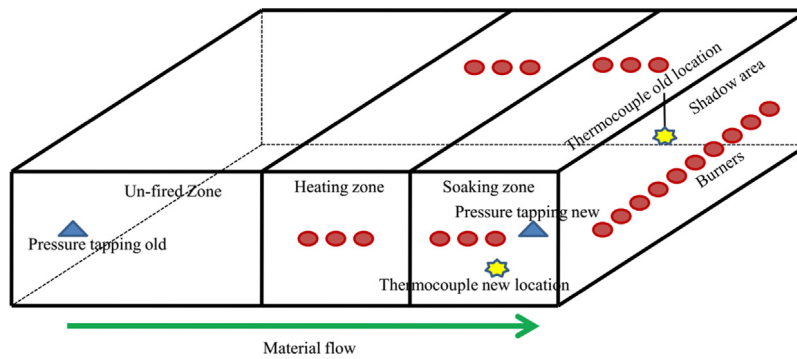


Fig. 1. Schematic of the Billet reheating furnace.

Instruments like infrared camera, fuel consumption monitor, surface thermocouple and other measuring devices are required to measure the above parameters.

3. Results and discussions

Energy efficiency studies and analysis have been carried out in the mill furnaces of SCSC, Thailand and energy balance has been established. Calculated energy savings amounts and efficiency values were compared with the values that were obtained after the application of modifications.

3.1. Plant level measurements and improvements

The results of the measurements and analysis that were realized in reheating furnaces are given below.

3.1.1. The thermocouple (TC) relocation and measurement correction

A critical observation of the position of the thermocouples in the roof revealed that the temperature measurements are not correct. An immediate measurement with hand-held pyrometer, the reading was found to be 1238 °C whereas the monitor at control room displayed 1165 °C. Display of a lower temperature by the thermocouple (TC) may have adverse consequences, namely, overheating of the billets, scale can melt and build up on the hearth, billets can be skewed and so on. The low temperature measurement is due to the wrong position of the TCs. The thermocouple positions were changed from the roof to the side wall. This was done during the MSD and trials were taken accordingly. This relocation restored the normal furnace thermal state and temperature profile. Subsequently, the temperature inside the furnace is cross checked with the help of a hand held pyrometer and found to be error-free.

3.1.2. Rectification of shortage in air supply

An intensive inspection revealed that all the burners are starving of air supply. A lot of smoke and reducing flame is observed during inspection. This indicates that incomplete combustion of the fuel gas is taking place. The air supply has been increased stoichiometrically and the flame front stabilized. This might be due to erroneous low temperature reported by TCs. Some amount of scale is fused and stuck to the hearth which is skewing the billets to some extent, were removed manually. The temperature and the fuel air ratio both are optimized as shown in Table 2.

This includes standard delay logic for controlling the furnace temperature. This will prevent the overheating as well as the molten scale deposition on the hearth. The normalcy of the burner flame front was restored after the air–fuel ratio control and the delay logic were properly implemented.



Fig. 2. The fused burner holes.

3.1.3. The furnace pressure tapping modifications

The furnace pressure tapping is on the charging side and maintaining a positive pressure of 0.8 mm wc. As a result, there is a high pressure in the soaking zone, which is an added problem with this. The temperature will always become higher and which is happening in actual practice. Fig. 2 shows fused burner holes. No flame was emerging out after this change. The holes are almost clogged and fused. This was a result of high pressure and temperature. In this case, the air and gas need to be throttled manually to correct the combustion.

3.1.4. Inter-billet gap re-adjustment

A big gap of 100 mm was maintained in between the billets. This should be ideally 35 to 50 mm. The billet to billet gap is reduced to 80 mm from 100 mm. This was the restriction of the lifting cylinder power that the total number of billets inside the furnace cannot exceed 80 at a time. This also improved the energy saving modalities. Fig. 3(a) and (b) show the actual inter-billet gaps prior and after the improvement.

3.1.5. Improved delay control logic

When there is an unforeseen mill delay, operator as a thumb rule, reduces the set points by 10 °C which is untenable in terms of operational practices. Improved Delay logic and shut down logic have been introduced into the system for the first time



Before improvement: 100 mm gap



After improvement: 80 mm gap

Fig. 3. Actual inter-billet gaps prior (a) and after (b) the improvement.**Table 2**
Zonal temperature and Air: Fuel ratio set points.

Size	Billet	Set point (°C)							
		Zone #1		Zone #2		Zone #3		Zone #4	
		Air: Fuel ratio	Temp set pt	Air: Fuel ratio	Temp set pt	Air: Fuel ratio	Temp set pt	Air: Fuel ratio	Temp set pt
RB9, DB10	Hot	14.56	Off	14.04	1170	10.4	1160	10.4	1160
	Cold	14.56	1050	14.04	1170	10.4	1160	10.4	1160
RB12, DB12, DB20	Hot	14.56	Off	14.04	1170	10.4	1160	10.4	1160
	Cold	14.56	1080	14.04	1170	10.4	1160	10.4	1160
RB15, DB16	Hot	14.56	Off	14.04	1170	10.4	1160	10.4	1160
	Cold	14.56	1080	14.04	1170	10.4	1160	10.4	1160

Table 3
(a) Delay logic introduced and (b) Shut down logic introduced.

(a) Delay logic introduced	
Delay (min)	Time for manual temp
60	30 min
90	50 min
120	70 min
180	90 min

(b) Shut down logic introduced	
Shutdown (h)	Time for shutdown RHF (h)
4	2.5
6	4
8	5.5
10	7

shown in Table 3(a)&(b). If there is a delay of 30 min, for the first 10 min, the temperature will be reduced by 50 °C; next 10 min, it will be maintained at that level and last 10 min will be used for heating up the billets to the initial level. This procedural improvement minimized the loss of unused fuel and eventually increased the energy saving. Further, the billet overheating could also be avoided.

3.2. Energy saving implementation strategy

The fuel consumption was reduced by 21% at SCSC furnace after implementing all the recommendations. All the points recommended were carefully studied and implemented smoothly by the respective teams without hampering the normal operation. The reduction in the billet gap from 100 to 80 mm has resulted in a 11% increase in the throughput of the furnaces. The gap can further be reduced to 50 mm if the hydraulic system is upgraded. Relocation of the thermocouple position and the pressure tapping resulted in a major improvement in the heating performance. It helped in measuring the furnace temperature correctly and eradicated uncertainties of measurements. It is found from the

comparative heat balance study (Tables 4 and 5), that the furnace has much higher capacity over the mill.

Most of the heat input is wasted because of the slow discharging particularly in the case of hot charging. Therefore, the ‘unaccounted loss’ is high and remains invariant, all through as reflected in the heat balance Figs. 4(a) and 4(b).

Considerable heat is lost when the billets are waiting inside the furnace to be discharged after getting ready for hot rolling. To reduce the unaccounted loss, the mill has to indicate the furnace to reduce the temperature for a specific period of delay time.

It is evident from the Figs. 5(a) and 5(b) that the fuel and the air consumption per ton of billets has been reduced after the proposed modifications were implemented in operating practices.

Fig. 6 depicts the air-fuel ratio before and after the proposed modification in the operating condition. This was quite high before modification as the zone 1 burner air was open but fuel was closed. Where as zone 2 & 3 were starving for air. This was adjusted later and standardized. The ‘Other losses’ like incomplete combustion losses, hidden losses, heat dissipation by moisture formation, etc. are assumed to be the same in both the cases before and after. It is important to reduce the temperature of the furnace in the case of hot charging. Energy saving opportunities have been determined as; thermocouple relocation, pressure tapping position changed to the soaking zone, reduction of billet to billet gap, introduction of delay logic and reduction in the temperature set points. Calculated energy savings amounts and efficiency values were compared with the values that were obtained after the applications and the techno-economic benefits are shown in Table 6.

4. Conclusion

As a result of all these improvements like thermocouple relocation, pressure tapping position changed to the soaking zone, reduction of billet to billet gap, introduction of delay logic and reduction in the temperature set points, a total amount of 0.1841 GJ/Ton energy saving has been achieved. The efficiency of the reheating furnace has been raised from 32.32% to 38.90%. Thus, a

Table 4
Heat balance figures (before modification).

Heat inputs	kJ/h	Heat outputs	kJ/h	%
Fuel combustion	59 266 666	Heat to charge material	19 160 890	26.23
Preheated air	11 267 713	Loss due to waste gas	19 974 515	27.34
Heat of exothermic reactions	2 525 976	Conduction through walls, roof, hearth	4 536 147	6.21
		Radiation through open doors	83 066	0.11
		Cooling water	2 344 608	3.21
		Other losses	5 844 827	8.0
		Unaccounted losses	21 116 302	28.9
Total	73 060 355		73 060 355	

Table 5
Heat balance figures (after modification).

Heat inputs	kJ/h	Heat outputs	kJ/hr	%
Fuel combustion	49 904 981	Heat to charge material	19 413 471	31.84
Preheated air	8 377 347	Loss due to waste gas	14 680 315	24.07
Heat of exothermic reactions	2 697 572	Conduction thru walls, roof, Hearth	3 306 232	5.42
		Radiation through open doors	83 066	0.13
		Cooling water	2 344 608	3.84
		Other losses	4 878 392	8.00
		Unaccounted losses	21 152 208	26.7
Total	60 979 900		60 979 900	

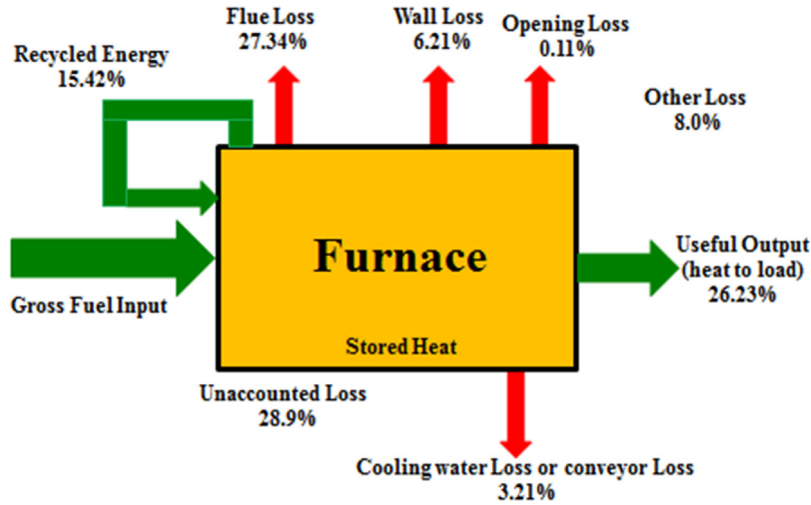


Fig. 4(a). Schematic of SCSC for the heat balance: Before modification.

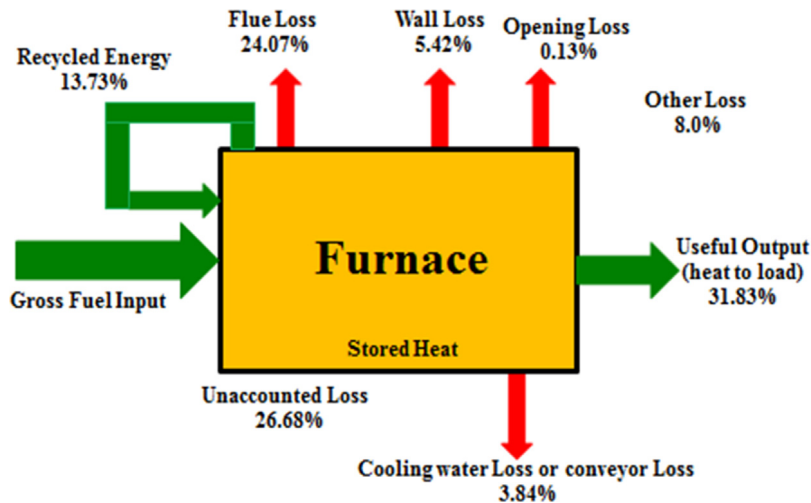


Fig. 4(b). Schematic of SCSC for the heat balance: After modification.

Table 6
Improved performance after modifications.

Items	Initial	After modification	Improved by
Fuel consumption	0.8744 GJ/T	0.6903 GJ/T	0.1841 GJ/T (21.05%)
Productivity	72 billets/Furnace	80 billets/Furnace	8 billets/Furnace (11.11%)
Furnace efficiency	32.32%	38.90%	6.58%

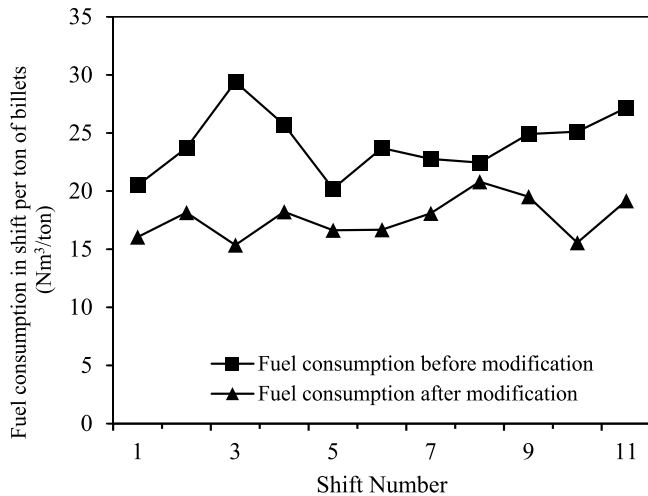


Fig. 5(a). Fuel consumption per ton of billets in shift.

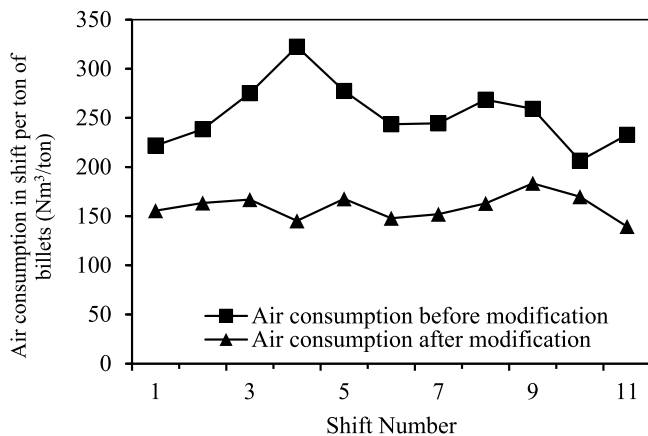


Fig. 5(b). Air consumption per ton of billets in shift.

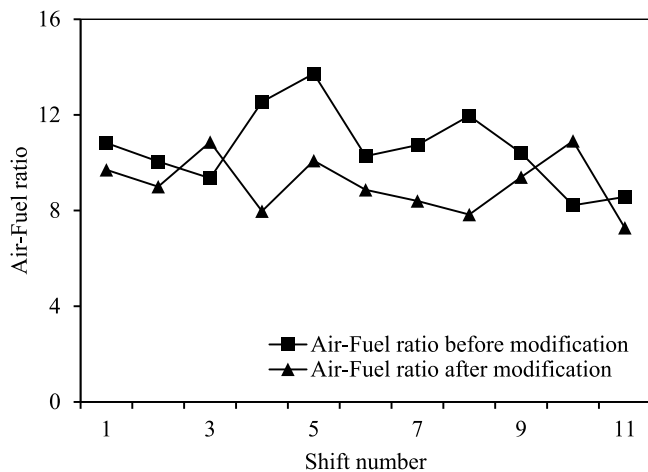


Fig. 6. Air-Fuel ratio before & after modification.

significant amount of energy saving and efficiency increment has been ensured. Several important parameters have been measured and detail heat balance studies have been conducted. The hidden losses are found scientifically and in an innovative way. Possible modifications had been identified and done. This resulted in more than 21% reduction in fuel consumption, a 11% increase in the productivity and total savings are more than 260 million rupees per year.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

We wish to express our deep sense of gratitude to the entire team at SCSC for their support which helped in completing the study in the plant.

References

- An, R., Yu, B., Li, R., Wei, Y.-M., 2018. Potential of energy savings and CO₂ emission reduction in China's iron and steel industry. *Appl. Energy* 226, 862–880.
- Arink, T., Hassan, M.I., 2017. Metal scrap preheating using flue gas waste heat. *Energy Procedia* 105, 4788–4795.
- Chakravarty, K., 2016. Improvement in production yield of Hot-rolled coil by controlling process cobbles. *J. Iron Steel Res. Int.* 23, 1035–1043.
- Chakravarty, K., Das, S., Singh, K., 2013. Identification and improvement in operating practices of reheating furnace to reduce fuel consumption in hot strip mill. *Ironmak. Steelmak.* 40, 74–80.
- Charles, X.U.C., Cang, D., 2010. A brief overview of low CO₂ emission technologies for iron and steel making. *J. Iron Steel Res. Int.* 17, 1–7.
- Chen, W.H., Chung, Y.C., Liu, J.L., 2005. Analysis on energy consumption and performance of reheating furnaces in a hot strip mill. *Int. Commun. Heat Mass Transfer* 32, 695–706.
- Demin, C., Lu, B., Dai, F.Q., Chen, G., Zhang, X., 2018a. Bottleneck of slab thermal efficiency in reheating furnace based on energy apportionment model. *Energy* 150, 1058–1069.
- Demin, C., Lu, B., Zhang, X., Dai, F., Chen, G., Liu, Y., 2018b. Fluctuation characteristic of billet region gas consumption in reheating furnace based on energy apportionment model. *Appl. Therm. Eng.* 136, 152–160.
- Enes, K., Kaya, D., Kiliç, F.Ç., Eyidoğan, M., Özkaymak, M., Taylan, O., Pedrycz, W., 2014. An energy efficiency analysis of an industrial reheating furnace and an implementation of efficiency enhancements methods. *Energy Explor. Exploit.* 32, 989–1003.
- Ghanbari, H., Helle, M., Saxén, H., 2012. Process integration of steelmaking and methanol production for suppressing CO₂ emissions—A study of different auxiliary fuels. *Chem. Eng. Process.: Process Intensif.* 61, 58–68.
- Han, S.H., Baek, Seung-W., Kang, S.H., Kim, C.Y., 2007. Numerical analysis of heating characteristics of a slab in a bench scale reheating furnace. *Int. J. Heat Mass Transfer* 50, 2012023.
- Han, S.H., Chang, D., Kim, C.Y., 2010. A numerical analysis of slab heating characteristics in a walking beam type reheating furnace. *Int. J. Heat Mass Transfer* 53, 3855–3861.
- Hasanbeigi, A., Arens, M., Price, L., 2014. Alternative emerging ironmaking technologies for energy-efficiency and carbon dioxide emissions reduction: a technical review. *Renew. Sustain. Energy Rev.* 33, 645–658.
- Hosseini, S.M., Saifoddin, A., Shirmohammadi, R., Aslani, A., 2019. Forecasting of CO₂ emissions in Iran based on time series and regression analysis. *Energy Rep.* 5, 619–631.
- Jenkins, B., Mullinger, P., 2011. *Industrial and Process Furnaces: Principles, Design and Operation*. Elsevier.
- Juanicó, L.E., González, A.D., 2008. Thermal efficiency of natural gas balanced-flue space heaters: Measurements for commercial devices. *Energy Build.* 40, 1067–1073.

- Kangvanskol, K., Tangthieng, C., 2014. An energy analysis of a slab preheating chamber for a reheating furnace. *Eng. J.* 18, 1–12.
- Karali, N., Xu, T., Sathaye, J., 2016. Developing long-term strategies to reduce energy use and CO₂ emissions—analysis of three mitigation scenarios for iron and steel production in China. *Mitig. Adapt. Strateg. Glob. Change* 21, 699–719.
- Kaya, D., Eyidogan, M., Ozkaymak, M., Turhan, F., Kilinc, E., Kayabasi, E., Sahin, Z., Sonverdi, E., Selimli, S., 2013a. Energy exergy efficiencies and environmental effects of mixed fuelled (solid+gas) industrial facility steam boiler. *J. Energy Inst.* 85, 194–201.
- Kaya, D., Eyidogan, M., Ozkaymak, M., Turhan, F., Kilinc, E., Kayabasi, E., Sahin, Z., Sonverdi, E., Selimli, S., 2013b. Energy exergy efficiencies and environmental effects of mixed fuelled (solid+gas) industrial facility steam boiler. *J. Energy Inst.* 86 (4), 194–201.
- Koymatcik, C., Ozkaymak, M., Selimli, S., 2018. Recovery of iron particles from waste water treatment plant of an iron and steel factory. *Eng. Sci. Technol. Int. J.* 21 (3), 284–288.
- Levenspiel, O., 1999. Chemical reaction engineering. *Ind. Eng. Chem. Res.* 38, 4140–4143.
- Lv, W., Sun, Z., Su, Z., 2019. Life cycle energy consumption and greenhouse gas emissions of iron pelletizing process in China, a case study. *J. Cleaner Prod.*
- Minxing, M.Si., Thompson, S., Calder, K., 2011. Energy efficiency assessment by process heating assessment and survey tool (PHAST) and feasibility analysis of waste heat recovery in the reheat furnace at a steel company. *Renew. Sustain. Energy Rev.* 15, 2904–2908.
- Neumann, Kolja, Gladyszewski, Konrad, Groß, Kai, Qammar, Hina, Wenzel, Dennis, Górak, Andrzej, Skiborowski, Mirko, 2018. A guide on the industrial application of rotating packed beds. *Chem. Eng. Res. Des.* 134, 443–462.
- Palacios, J.-L., Fernandes, I., Abadias, A., Valero, A., Valero, A., Reuter, M.A., 2019. Avoided energy cost of producing minerals: The case of iron ore. *Energy Rep.* 5, 364–374.
- Paulrud, S., Nilsson, C., 2001. Briquetting and combustion of spring-harvested reed canary-grass: effect of fuel composition. *Biomass Bioenergy* 20, 25–35.
- Petchers, N., 2003. Combined Heating, Cooling & Power Handbook: Technologies & Applications: An Integrated Approach to Energy Resource Optimization. Fairmont Press.
- Rachel, M.L., Pauliuk, S., Allwood, J.M., Müller, D.B., 2013. The roles of energy and material efficiency in meeting steel industry CO₂ targets. *Environ. Sci. Technol.* 47, 3455–3462.
- Reyes, F., Luyben, W.L., 2000. Steady-state and dynamic effects of design alternatives in heat-exchanger/furnace/reactor processes. *Ind. Eng. Chem. Res.* 39, 3335–3346.
- Steinboeck, A., Wild, D., Kiefer, T., Kugi, A., 2010. A mathematical model of a slab reheating furnace with radiative heat transfer and non-participating gaseous media. *Int. J. Heat Mass Transfer* 53, 5933–5946.
- Thakur, P.K., Prakash, K., Muralidharan, K.G., bahl, V., Das, S., 2015. A review on: efficient energy optimization in reheating furnaces. *Int. J. Mech. Prod. Eng.* 3, 18–24.
- Trinks, W., Mawhinney, M.H., Shannon, R.A., Garvey, J.R., Reed, R.J., 2004. Industrial Furnaces. John Wiley & Sons.
- Zhang, X., Han, Y., Sun, Y., Lv, Y., Li, Y., Tang, Z., 2019. An novel method for iron recovery from iron ore tailings with pre-concentration followed by magnetization roasting and magnetic separation. *Miner. Process. Extr. Metall. Rev.* 1–13.
- Zhao, J., Zuo, H., Wang, Y., Wang, J., Xue, Q., 2019. Review of green and low-carbon ironmaking technology. *Ironmak. Steelmak.* 1–11.