AN INVESTIGATION FOR GENERATION OF ENERGY CONSERVATION MEASURES FOR SPONGE IRON PLANTS USING PROCESS INTEGRATION PRINCIPLES

Anil Kumar Prasad[1], Radha Krishna Prasad[2] & Shabina Khanam[3,*]
[1,2] Department of Mechanical Engineering, National Institute of Technology Jamshedpur- 831001, Jharkhand, India
[3] Department of Chemical Engineering, National Institute of Technology Rourkela-769008, Orissa, India
*E-mail address: shabinahai@gmail.com, skhanam@nitrkl.ac.in
Phone No. +91-661-2462267, Fax No. +91-661-2462999

ABSTRACT
During the operation, a tremendous amount of heat is generated in the coal based sponge iron plant and a significant part of this heat associated with the waste gas, remains unutilized. While utilizing this heat in the process the energy demand of the process may be reduced, which decreases the coal consumption as coal is the only source of energy in this plant. Further, it is seen that existing plant consumes 5.57 times more energy than theoretical value. This information advocates the basic motivation of the present study. To utilize the heat associated with waste gas pinch analysis is applied on the actual data of plant and identified three feasible cases for energy conservation. For these cases capital investment required for retrofitting as well as total profit in terms of coal and water saving are compared and best design is selected. The best design includes preheating of air as well as feed material to rotary kiln and cooling of kiln outlet using waste gas. It consumes 12.5% less coal in comparison to existing system. The payback period of the best design is 56 days only. This design also satisfies the practical conditions of the process.

Keywords: *Sponge iron plant, Heat integration, Coal consumption, Capital cost, Payback period*

1. INTRODUCTION

Sponge iron is not soft and spongy but a metallic mass with honeycomb structure having minute holes all over the surface and bulk. Since the last few years, sponge iron has emerged as a sound alternative raw material for steel making through the electric arc furnace (EAF) route. Seeing its tremendous potential in iron and steel making, Government have recognized sponge iron as vital sector for the growth of Indian steel industry. Again, India is fortunate to have high reserves of iron ore of good quality and large resources of non-coking coal.

Sponge iron manufacturing unit looked very profitable since the beginning of nineties. However, with the liberalization of import duties of scrap, increase in the input cost of raw material and comparatively decrease in the selling price, sponge iron industry found difficult to survive in the market. Even today, when the situation has improved, sponge iron industry is passing through several problems like lack of optimization of main equipments and energy savings schemes, etc. So, this field appears very relevant and needs research and development.

Many investigators considered the process of sponge iron manufacturing and suggested improvement in that [1, 2, 3, 4]. It is found that during the operation in the coal based sponge iron plant, a tremendous amount of heat is generated and a significant part of this heat associated with the waste gas, remains unutilized.

Jena et al. [5] proposed a quantitative analysis based on waste gas, gas composition, dust loss, air requirement and efficiency of the process. They found that due to chemical reactions and combustion the heat generated inside the kiln is 174.28 GJ/h and the heat value of the coal input is 323.2 GJ/h resulting in a thermal efficiency of the process to be 53.9%. Considerable amount of heat is lost in the waste gas which is about 33% of heat generated in the kiln. The authors suggested that heat in waste gas may be recovered by putting a waste heat recovery system for generation of power.

Bandyopadhyay et al. [6] discussed that if very high volatile matter coals are used, most of the matter in feed coal is lost at the kiln mouth when coal encounters counterflowing hot waste gases. The major problem mentioned was that 30-40% of the total energy joins the waste gases. Elsenheimer and Serbent [7] also mentioned that energy contained in waste gas in form of sensible or chemical energy amounts up to 40% of the energy fed in form of coal. They proposed a number of options to recover energy of waste gas but did not show that how much energy can be saved by installing these options and what are their practical implications.

Ebrahim and Ali [8] studied the thermal analysis of sponge iron preheating using waste energy of 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. Based on simulation results it is found that the energy consumption in EAF can be reduced up to 14% and productivity can be increased up to 13%.

Biswas et al. [9] and Eriksson and Larsson [10] suggested improvements in energy efficiency by modifying the rotary kiln design. Recently, Mignard and Pritchard [11] reviewed the sponge iron process for the storage and transmission of remotely generated marine energy.
The literature indicates that for Indian sponge iron industries the power consumption ranges from 45-130 kWh/t [12]. Significant improvements in decreasing energy consumption were achieved in gas based direct reduction processes. However, for coal based processes potential for such savings is required. Although many plants have acquired the desired level of operational efficiency but from energy point of view various units is below optimum limit. The principal cost factor in direct reduction is energy cost as energy requirement for rotary kiln processes ranges between 14.63 GJ/t to 20.9 GJ/t [13].
It is therefore understandable that energy questions are always important in these plants and hence, one should integrate the heat in these industries effectively. Thus, in the present paper an approach is discussed to utilize the heat of waste gas for preheating the raw material. As a result the reduced amount of coal is predicted. The equipments required for retrofitted process are suggested and their economic analysis is also presented.

2. COAL BASED SPONGE IRON PLANT: A CONVENTIONAL PROCESS

The process flow diagram of conventional coal based sponge iron plant is shown in figure 1. The operating data, shown in figure 1, is taken from a typical Indian coal based sponge iron plant where iron ore, feed coal and dolomite are fed to the rotary kiln. A separate conveyor collects different size fractions of coal for injection into the kiln with the help of pressurized air from discharge end side. All along the kiln length air is injected through air fans and each of them can be adjusted separately. Further, air is injected at the kiln outlet by central burner pipe, which during normal operation serves as process air inlet.

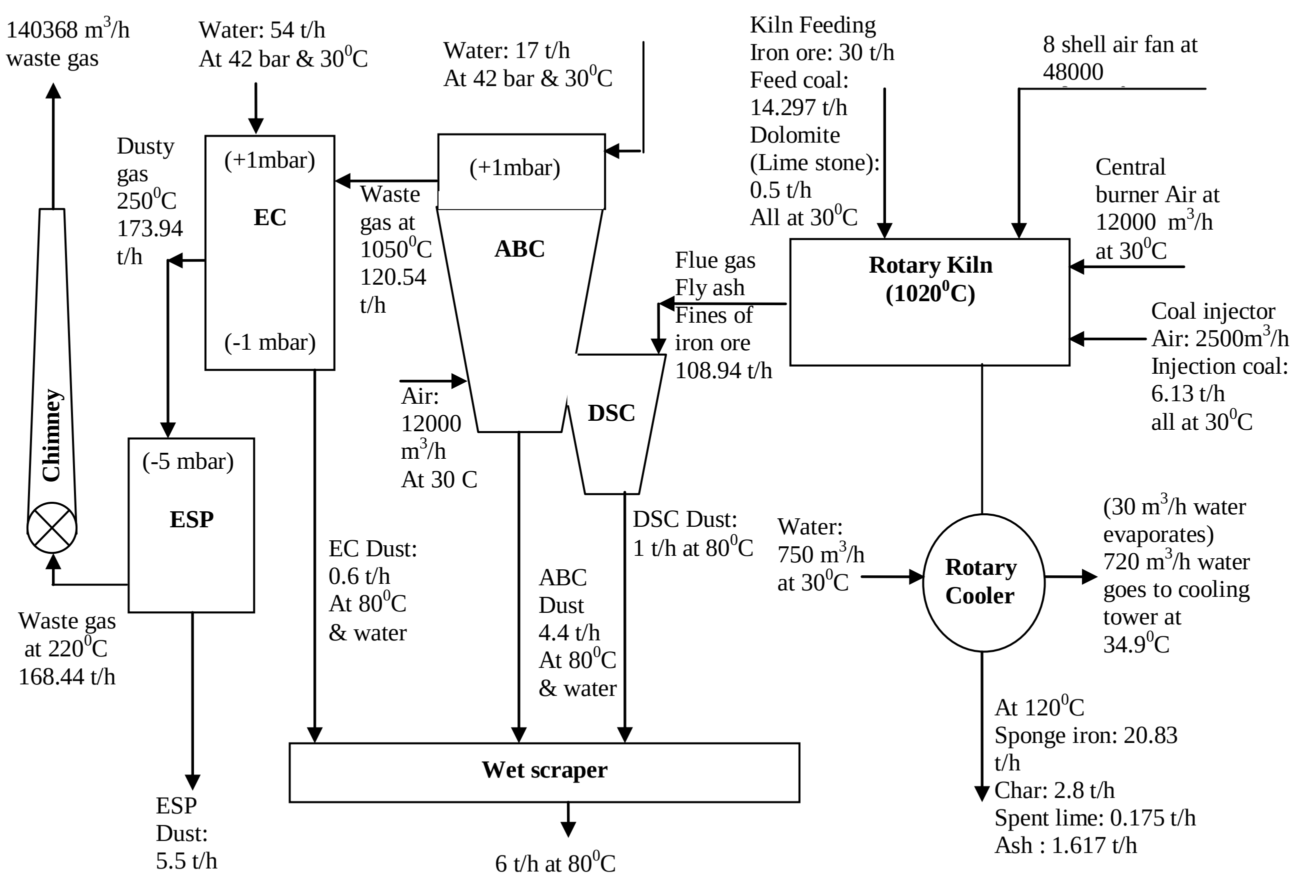

Figure 1. Conventional sponge iron plant flow diagram

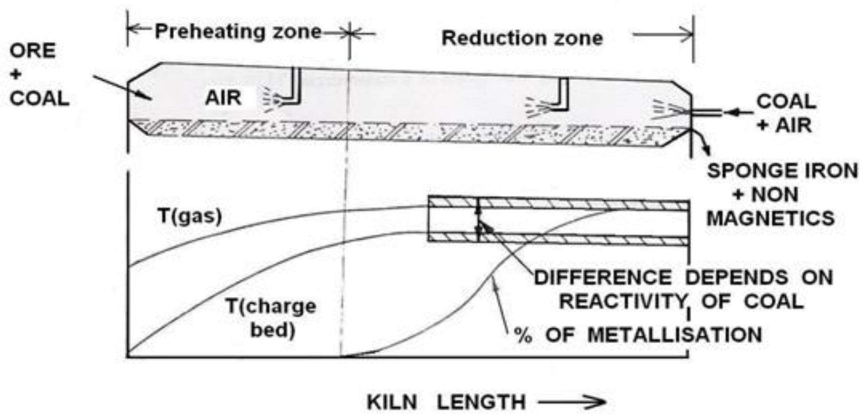

Figure 2. Principle of counter kiln operation

The inside kiln is lined with refractory and supported on three piers called support rollers with an inclination of 2.5%. Rotation is given by the girth gear. Due to its inclination and rotation material in the bed of the kiln moves along the axis. Both end of the rotary kiln is provided by the mechanical air sealing so that no ingress of air takes place. As the charge moves through the kiln, it is heated by the gases which flow in opposite direction to the charge. Inlet side of the kiln, blowing of a controlled amount of air into the material charge increases the material temperature by direct combustion of volatiles within the charge.

The first section approximately half of the kiln is called preheating zone where iron ore, coal and dolomite are heated to reaction temperatures and the second half is the reduction zone as shown in figure 2. In the preheating zone, the moisture of the materials is driven off along the waste gas. The volatiles of the coal are to one part escaping into the gas space above the material bed and to the other part directly burned within the material charge where they are used for direct heat up. The volatiles in the gas space are burned by the air admitted through the air pipes and thus supply the main energy source for heating up the kiln charge. In the reduction zone, the main portion of the oxygen contained in the iron ore, is removed leaving metallic iron and very few iron oxide behind. The difference of the temperature of the free gas T (gas) and bed material T (charge bed) is shown in figure 2 along the length of the kiln. It is responsible for heating bed charge and metallization of product. Plot of the % of metallization is shown in figure 2. It indicates that the reduction of iron ore starts in the reduction zone and required metallization of the product is achieved at the discharge end of the kiln. The reduced product from the kiln is indirectly cooled in a rotary cooler.

The waste gas in the kiln flows in the opposite direction to the feed material movement. The flow is maintained by induction fan mounted before the chimney. The waste gas coming out from the rotary kiln is processed by the different equipment before it leaves to the open atmosphere. Generally, waste gas consists of N_2, CO_2, CO, H_2, H_2O, O_2 and CH_4. It comes out of the kiln at a temperature about 900^0C and then is taken to after burner chamber (ABC) and a horizontal dust settling chamber which is located beneath the ABC. Dust settling chamber (DSC) reduces the waste gas velocity, removes large dust particles by gravity, retards pressure fluctuation and achieves uniformity of waste gases with regard to temperature and concentration of combustible. At the end of DSC the waste gases change their direction of flow and move upward into combustion area of ABC. Here combustibles are mixed with fresh excess air and burnt completely to acquire temperature in a range between 950^0C to 1050^0C approximately.

To removal dust particles and toxic components from waste gas water is sprayed in the ABC. For this purpose eight to ten numbers of water gun is fitted along the different height. The water guns hold a nozzle at the discharge end for atomization. The pressurized water coming out from the guns falls on the waste gas carrying dust particle. It results the increase in weight of dust particles that helps it to settle down.

The evaporating chamber (EC) is connected with the ABC as shown in figure 1. Here, the waste gas is quenched as temperature of waste gas needs to be brought down to a workable limit for downstream equipment. For quenching eight - ten numbers of water guns are provided at the top position of EC around the circumference at the same height. Water coming out from the guns is sprayed to reduce the temperature of waste gas at desired level. The bottom part of the EC, dust settling chamber and ABC is attached with wet scraper to collect the dust.

Further, waste gas coming out from the EC, is entered the electrostatic precipitator (ESP) for final purification. The desired temperature of the waste gas is to be maintained below 250^{0}C. ESP is considered to be the most effective dust collector in industries. It has gained acceptance over other collectors due to its various advantages like low pressure drop, low sensitivity at high temperature and aggressive gases, high collection efficiency and low maintenance. ESP exit is connected to the chimney through the waste gas carrying duct. Induced direct fan placed before chimney. After ESP, the filtered waste gas goes to the surroundings through Chimney.

2.1. Cost Components for One Tonne Production of Sponge Iron

The cost of sponge iron production varies with different inputs such as iron ore, coal, dolomite, fuel, maintenance, depreciation, power, etc. The costs of these inputs, taken directly from the plant, for one tonne production of sponge iron are drawn in figure 3. It is clear from this figure that 31.8% cost is due to the coal which is a considerable amount.

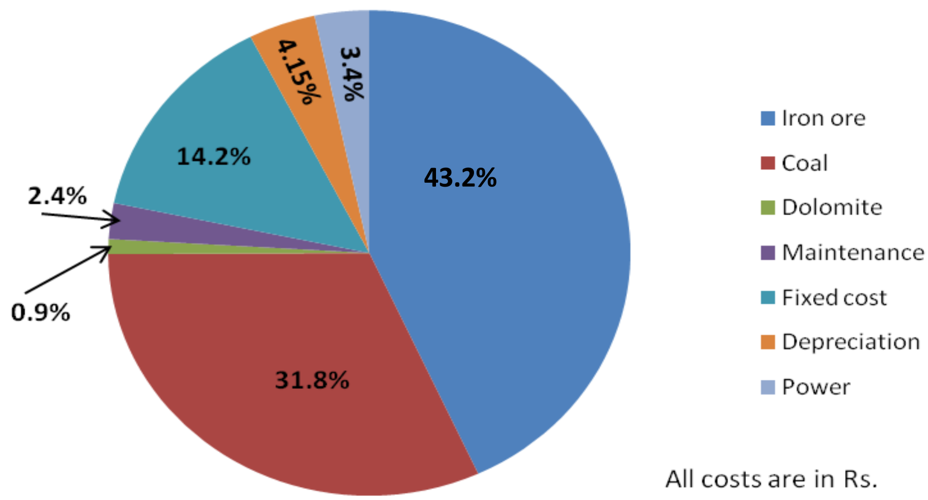

Figure 3. Cost components for one tonne production of Sponge iron

In fact for such plants coal is the only source of energy as it is generated by combustion of coal. However, the energy demand of the process can be reduced by proper integration of heat within the process which results less energy to be supplied by coal. Consequently, coal consumption is decreased which also reduces cost of coal per tonne production of sponge iron. Thus, cost component of coal in figure 3 is directly related to the energy requirement.

2.2. Energy Requirement

Sponge iron is produced by direct reduction of iron ore carried out in rotary kiln which involves following chemical reactions [Biswas et al., 2003]:

$$1/2\ Fe_2O_3 + 3/2\ CO = Fe + 3/2\ CO_2 \quad -12{,}866\ \text{kJ/kmol} \tag{1}$$

$$1/3\ Fe_3O_4 + 4/3\ CO = Fe + 4/3\ CO_2 \quad -3{,}904\ \text{kJ/kmol} \tag{2}$$

$$FeO + CO = Fe + CO_2 \quad -16{,}108\ \text{kJ/kmol} \tag{3}$$

$$FeO + C = Fe + CO \quad +156{,}482\ \text{kJ/kmol} \tag{4}$$

Eq. 4 indicates the heat required for desired rate of reduction of iron oxide to iron. CO thus generated by Eq. 4 is utilized either for further reduction of iron ore vide Eqs. 1 to 3 or for combustion ($2CO + O_2 \rightarrow 2CO_2$) and subsequent heating of overbed of material. It is revealed from Eq. 4 that 56 kg of sponge iron requires approximately 12 kg of carbon and 156482 kJ/kmol of endothermic heat. Therefore, for the endothermic process heat (kJ/h) requirement is:

$$Q_p = (156482/56)\ m_s \tag{5}$$

Total theoretical energy requirement for reduction of 30 tonne ore is found as 8.4×10^7 kJ using Eq. 5. However, the actual energy consumed in conventional plant can be computed as:

$$\text{Actual energy consumed} = m_c \times NHV \qquad (6)$$

Based on Eq. 6, 4.68×10^8 kJ is supplied to the process which is 5.57 times more than the theoretical value. This information advocates the basic motivation of the present study. One of the possible ways to reduce energy consumption is integrate the heat in the process and thus, minimize the heat demand from outside source.

3. HEAT INTEGRATION IN SPONGE IRON PLANT

It appears worth interesting to give a fresh look on the existing system with a view to retrofit it which facilitates the utilization of the heat. The possible areas of the flow diagram, shown in figure 1, where energy is being lost and can be conserved, are as follows:

1. An appreciable portion of the energy is being lost in the rotary kiln through untapped waste gas. The detail computation of heat content of waste gas, reported in work of Prasad et al. [14], shows that 43.5% of total energy produced in the kiln is being lost with waste gas. This available heat of gas can be utilized for the process.
2. Hot sponge iron is being cooled from 1020°C to 120°C using water in the rotary cooler. For this purpose water is used through an indirect heat exchanger and the vapor generated from it is at considerably low temperature (34.7°C) that goes directly to atmosphere. The energy associated with hot sponge iron can be tapped for better process use.
3. Clean waste gas is generated in ESP from where it goes to the chimney at the temperature of 220°C. From the chimney waste gas goes to the atmosphere, which is also a loss of considerably high temperature heat.

Thus, these are a number of potential areas where energy is being lost and not tapped. This energy can be conserved and utilized in the process through proper heat integration to decrease the energy bills of the industry. For this purpose the stream data is extracted from figure 1 and presented in table 1.

Table 1. Stream data of existing process

Steam	Type	T_s	T_t	C (J/kg◦C)	Flow (kg/s)	MC (kW/C)
Kiln Outlet	h1	1020	120	678.03	7.09	4.81
Water	c1	30	34.96	4187	208.33	872.29
Vapor	h2	34.96	33.96	1864	8.33	15.53
Wet scrapper out	h3	80	30	881.33	1.67	1.47
ESP out	h4	125	30	896.42	1.53	1.37
waste gas	h5	220	30	1140	46.78	53.33

Here, outlets streams of wet scrapper and ESP are considered as hot streams which cool down to ambient temperature (30^0C). Based on this data following possible cases for energy conservation are identified:

Case-1: Existing system as shown in table 1

Case-2: Existing system without water and vapor streams. This case is an improved version of Case-1 where efforts are being made to save waste energy of the process. In this case waste gas, which is exiting from ESP as shown in figure 1, is used to cool kiln outlet. In fact, in real situation the kiln outlet stream is being cooled using cold water (stream c1 in table 1). In this case waste gas behaves as cold stream (from 70^0C to 161.15^0C) and is used to cool kiln outlet.

Case-3: In this case air preheating is considered over and above the Case-2. In other words, Case-3 is Case-2 plus provision for air preheating. The waste gas, which is exiting from ESP as shown in figure 1, is available at 220°C and need to be cooled down below 60°C. This was done by dissipating its heat to atmosphere in Case-2 where, it is cooled inside the duct. A better alternative will be to recover this heat by putting this to use for preheating the air. Here, air in included in table 1 as a cold stream from 30^0C to 170^0C. Here cold waste gas is used to cool kiln outlet.

The energy requirement for these cases is computed using pinch analysis [15], which is a tool for process integration. However, the present problem is somewhat different than common problems that are tackled using Pinch Technique. This difference is explained through table 2.

The typicality of the present problem is that coal and air (used for burning purpose) fulfill the heating requirement of the process and at the same time these serve as process streams also. As hot utility is supplied by burning of coal with air, once the amount of hot utility changes the coal and air requirements also change. Due to this fact, flow rates of process streams (mainly coal and air) vary during solution of the problem as pointed out in third row of table 2. This necessitates trial and error computation techniques to solve the problem.

Table 2. Difference between common problems which are tackled through Pinch Technology and the present problem

Particular(s)	Common problems	Present problem
Process streams	Generally with gas and liquid phase	All the three phases i.e. gas, liquid & solid are involved as process streams
	Flow rate remains fixed	Flow rate changes when heat integration is applied
Hot utility	Steam (VHP, HP, MP and LP), flue gas, hot oil	Coal and air (The heat is being imparted to the process by combustion of coal in the presence of air)
	Hot utility can never be a process stream	Hot utilities (Coal and air) are process streams also
Cold utility	Used for heat integration	Not used for heat integration as streams which require cold utility releases its heat to atmosphere
Solution technique	Pinch technology	Pinch technology approach with trial and error computation

The hot utility for all cases is zero; however, cold utility for each is shown in table 3. The cold utility for these cases is almost equal and it is due to outlet streams of wet scrapper (h3) and ESP (h4). It is not feasible to recover heat available in these streams as these are dust streams and may foul the surface of exchanger considerably. Thus, for heat integration these streams are neglected.

Table 3. Cold utility requirements for three cases

Cases	Cold utility, kW
Case-1	9869.2
Case-2	198.8
Case-3	198.8

3.1. Model of Coal Consumption for Process

In the sponge iron plant the only source of energy is coal which is produced by its combustion. So, coal consumption is decided by energy demand of the process which depends on hot utility requirement, heat gained by the incoming air and bed of materials, heat required for the endothermic reaction process for reduction to continue, heat lost through the rotary kiln wall, heat gained by coal and latent heat required by moisture of feed material to evaporate. The estimation of total heat requirement for conventional process consists of the following expressions:

Hot utility requirement

In the present work hot utility requirement, Q_{hu}, is computed using pinch analysis [15]. This utility is supplied by combustion of coal.

Heat gained by the inlet air and bed of material

In the preheating zone inlet air and iron ore is heated upto 1020 and then reduction takes place in the respective zone. The sensible heat gained by air and ore is supplied by combustion of coal and computed using following equations.

$$Q_a = m_a C_a (T_p - T_i)$$

$$Q_s = m_s C_s (T_p - T_i)$$

Heat required for the reduction process to continue

Heat requirement is computed using Eq. 5.

Heat lost through the kiln wall and refractory [5]:

$Q_{loss}=2\pi DL\times h_r$

The actual heat lost through the wall includes the heat lost through the kiln shell, inlet and outlet hoods, post combustion chamber and inlet area of the cooler. Therefore, the total heat loss is assumed as twice as that of the kiln.

Heat gained by coal

$Q_c = m_c C_c (T_p – T_i)$

Heat required for removing moisture of feed material

The average moisture contents in coal and iron ore are 13% and 2%, respectively, by weight in Indian conditions [1] and heat required to remove it is computed as:

$Q_m = m_m \times \lambda$

$Q_m = (0.02\ m_s+ 0.13\ m_c) \times \lambda$

Assume that the combustion efficiency is 70%. It is considered as 70% of total fixed carbon available in non-coking coal burns completely to give out the heat and remaining 30% do not burn. The major fraction of this unburnt carbon is lost to the atmosphere through waste gas as smoke, and rest is discharged with sponge iron from the rotary kiln. The final empirical relation for estimating coal requirement is:

$Q_{hu} + Q_s + Q_a + Q_p + Q_{loss} + Q_c + Q_m = m_c\, NHV\ (0.7)$

$$\text{Or, } Q_{hu} + Q_s + Q_a + Q_p + Q_{loss} + 0.02\ m_s\times\lambda = m_c\,[NHV\ (0.7)-C_c(T_p-T_i)-0.13\times\lambda] \qquad (7)$$

The value of m_c can be predicted from Eq. 7 considering the NHV of coal as 22930.5 kJ/kg. The property data of air, ore and coal are constant and taken from literature [16, 17].

4. RESULTS AND DISCUSSION

Coal consumption for Case 1, 2 and 3 are computed using Eq. 7 and results are summarized in table 4. For these cases air of same amount, as shown in figure 1, is considered. In fact, in the process air requirement for combustion is depemdent on coal consumption so when it reduces inlet air requirement also decreases. Based on trial and error method actual amount of air is computed which gives actual coal consumption as shown in table 4.

In this process operating cost depends on coal and water requirements. The costs of coal and water are Rs 2500/t and Rs 60/t, respectively. Based on these values the operating cost for all cases are found and presented in table 4. It shows that maximum saving of 5.4%, 91.3% and 47.6% are found in coal consumption, water requirement and operating cost for Case-3 in comparison to the existing system.

Table 4. Coal and water requirements per hour basis

Cases	Coal cons., t	Water, t	Actual coal cons., t	Operating cost, Rs
Case-1	20.424	821	20.424	100322.1
Case-2	20.424	71	20.424	55322.13
Case-3	19.6	71	19.325	52571.75

While integrating heat in Case 2 and 3 a few additional equipment are required which are mentioned in table 5. This table does not include the equipment for Case-1 as it is the existing system where no integration is carried out. For Case-2 and 3 capital costs of gas-solid heat exchanger (double pipe) and gas-gas exchanger (shell and tube), shown in table 5, are taken from the work of Prasad et al. [14] and Shenoy [18], respectively. In all these cases production of sponge iron remains constant, thus, reduced amount of coal and water show the gain in the process. The profit and payback period of two cases are also shown in table 5. The results of case-2 and 3 based on data shown in table 4 and 5 are discussed in the subsequent sections.

Table 5. Economic data for three cases

Cases	Water, t/h	Actual coal cons. t/h	Capital cost		Profit Rs/day	Payback, days
			Equipment required	Cost, Rs		
Case 3	71	20.424	S-G heat exchanger	39913902.53	972000	41
Case 7	71	19.325	G-G heat exchanger	9418385.34	1031408	48
			S-G heat exchanger	49332287.87		

4.1. Case-2

1. In this case waste gas is used to cool kiln outlet. It reduces water requirement by 91.3% in comparison to existing system as shown in table 4.
2. Exit of kiln is to be cooled from 1020^0C to 120^0C which require waste gas to be entered at 70^0C as 50^0C temperature difference is required for heat transfer between gas and solid (Linnhoff et al., 1982). However, waste gas is available at 220^0C. This temperature cools down to 70^0C due to heat loss while passing it through a non-insulated duct. The detailed design of duct is shown in the work of Prasad et al. [19].
3. For this purpose an indirect gas-solid heat exchanger is required which can be designed based on the work of Prasad et al. [14].

The coal consumption for this case remains unchanged in comparison to existing system as integration of heat is not done between streams which are entering and exiting from the process. Here, waste gas and kiln exit are outlet streams of process. Thus, energy demand of process also remains unaltered.

4.2. Case-3

1. Air is preheated from 30^0C to 170^0C using waste gas. For this purpose 59738.8 m^3/h waste gas is used which is cooled from 220^0C to 80^0C as 50^0C temperature difference is required for transferring heat between air and waste gas [15]. A gas-gas shell and tube heat exchanger is employed as additional equipment with heat transfer coefficient and area as 50 $W/m^2\ ^oC$ [20] and 847.5 m^2, respectively. Due to air preheating by waste gas 5.4% coal consumption is reduced.
2. Waste gas of 59738.8 m^3/h cools to 80 ^{0}C by supplying its heat to air. Further, this waste gas is mixed with remaining gas of 69760.4 m^3/h (at 220^0C). Then it is heated from 70^0C to 151.15^0C by taking heat from kiln outlet. Consequently, the kiln outlet is cooled down to 120^0C. Waste gas achieves 70^0C by moving through the non-insulated duct. Here, 91.3% water consumption can be reduced. For this purpose a gas-solid heat exchanger as used for Case-2 is employed.

Table 5 shows that minimum and maximum payback periods of 41 and 48 days are observed for Case-2 and 3, respectively. Based on this information Case-2 should be selected as best design. However, the difference between minimum and maximum periods is only 7 days which is not appreciable. Thus, Case-3 may be selected as best option as after 48 days of operation it will provide maximum profit in terms of coal and water saving. The process flow diagram for Case-3 is shown in figure 4 where modification in the design is drawn with bold lines.
Further, it can be seen from figure 1 that waste gas exiting the ABC is at considerably high temperature which is cooled down from 1050^0C to 250^0C by spraying water in EC. However, high temperature heat of waste gas can be used in the process. For this purpose a modification is identified apart from data, shown in table 1. It is referred as Case-4. Coal consumptions for this case are computed using Eq. 7. The modifications are discussed in the following points:

1. Air is preheated up to 300^0C using 18776.9 m^3/h waste gas. In this case air cannot be heated more than 300^0C as it may ignite coal in injector. Waste gas is cooled down from 1050^0C to 250^0C. A gas-gas shell and tube heat exchanger of 1522.2 m^2 area is required.
2. Further, waste gas of 2332 m^3/h is used to preheat the feed to kiln (iron ore, feed coal and dolomite) from 30 to 120^0C. It cannot be heated beyond 120^0C due to conveying problem. Consequently, waste gas cools to 250^0C. For this purpose a gas-solid heat exchanger is placed as additional equipment. Design and cost of this heat exchanger is carried out in the similar manner as shown by Prasad et al. [14].
3. Again injection coal is heated upto 120^0C as beyond that CO is generated from coal. Waste gas 612.7 m^3/h is used for this purpose. It also requires a gas-solid heat exchanger as additional equipment.

4. Remaining amount of waste gas enters EC to cool down. It requires only 37 m^3/h water.
5. Waste gas is also used to cool kiln outlet from 1020^0C to 120^0C using a gas-solid heat exchanger similar to Case-3.

The modified design of Case-4 consumes 93.4% and 12.5% less water and coal in comparison to the existing system. It gives total profit of Rs 1128602/day. However, to achieve this 3 gas-solid and one gas-gas heat exchangers are required which gives investment of Rs 62106561/-. Total payback period is 56 days which is only 8 days more than that for Case-3. This modification reduces load on EC significantly as amount of waste gas handled by it declines substantially. Moreover, mass balance on the process shows that less amount of waste gas is generated here in comparison to Case-3 which consequently, releases less waste gas to the atmosphere.
Further, the energy requirement for Case-2, 3 and 4, computed using Eq. 6, are compared with the theoretical value, predicted using Eq. 5, and summarized in figure 5. The energy requirement in the reduction process is theoretically minimum value which cannot be achieved completely in practice. However, it can be approached. For the existing system 5.57 times more energy is required which is reduced up to a value of 4.9 for Case-4 as shown in figure 5. Amongst all the cases, Case-4 consumes minimum energy with payback period of 56 days which is close to that for Case-3. Therefore, Case-4 is selected as final retrofitted plant and shown in figure 6.

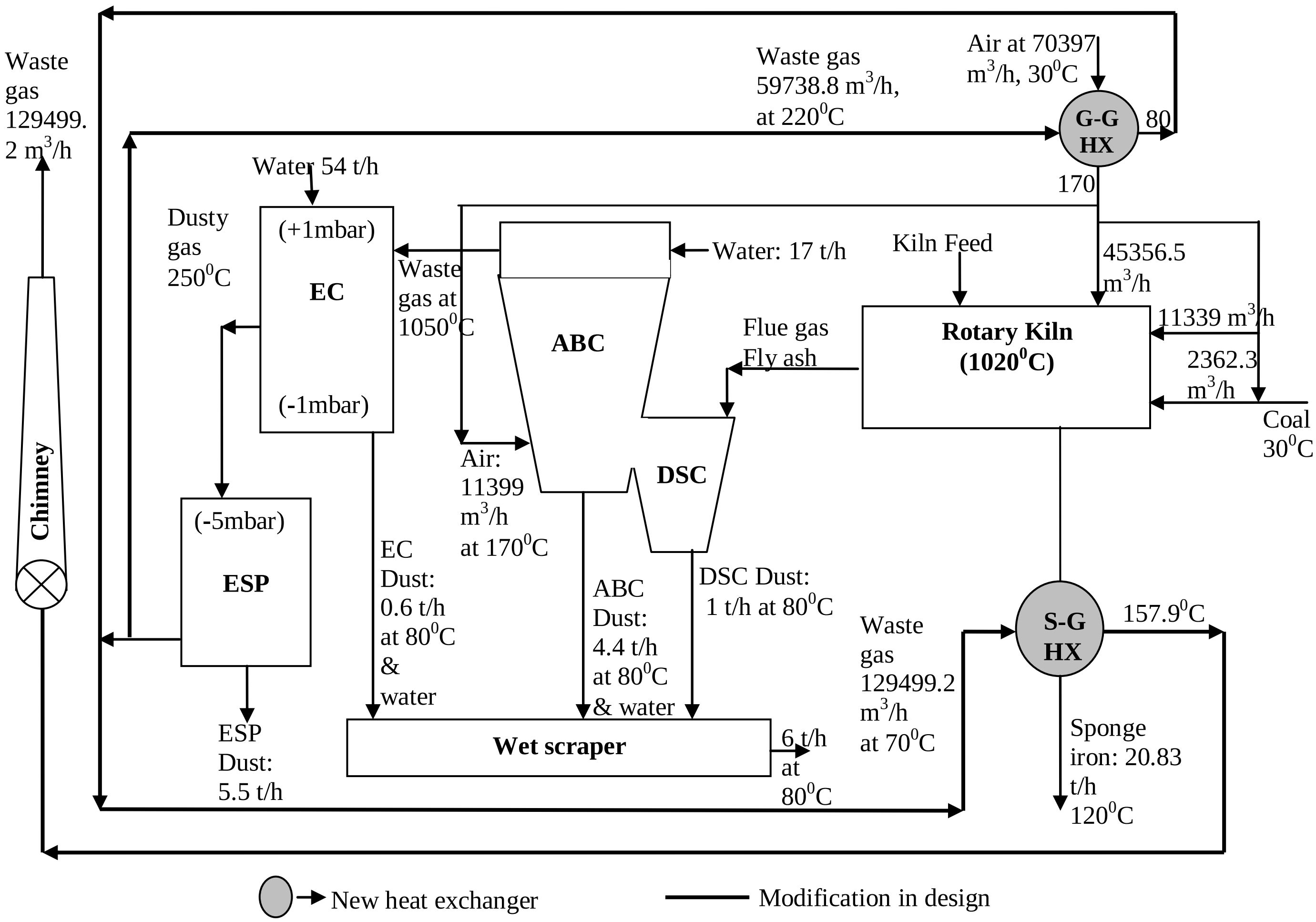

Figure 4. Process flow diagram for Case-3

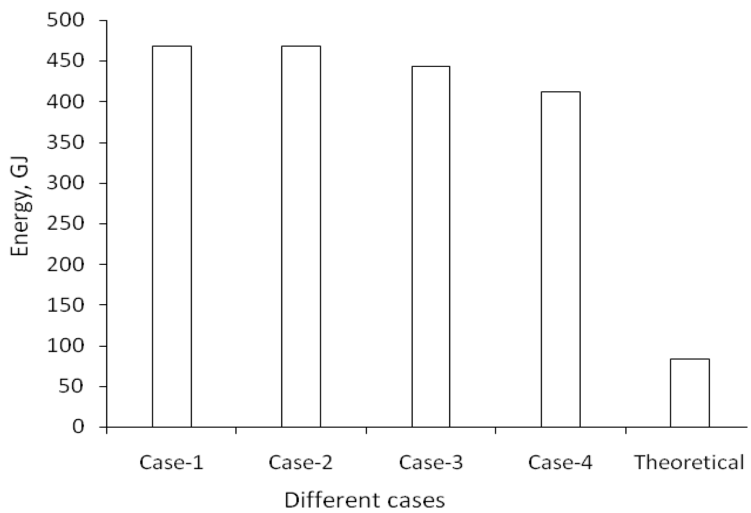

Figure 5. Energy requirement by difference cases

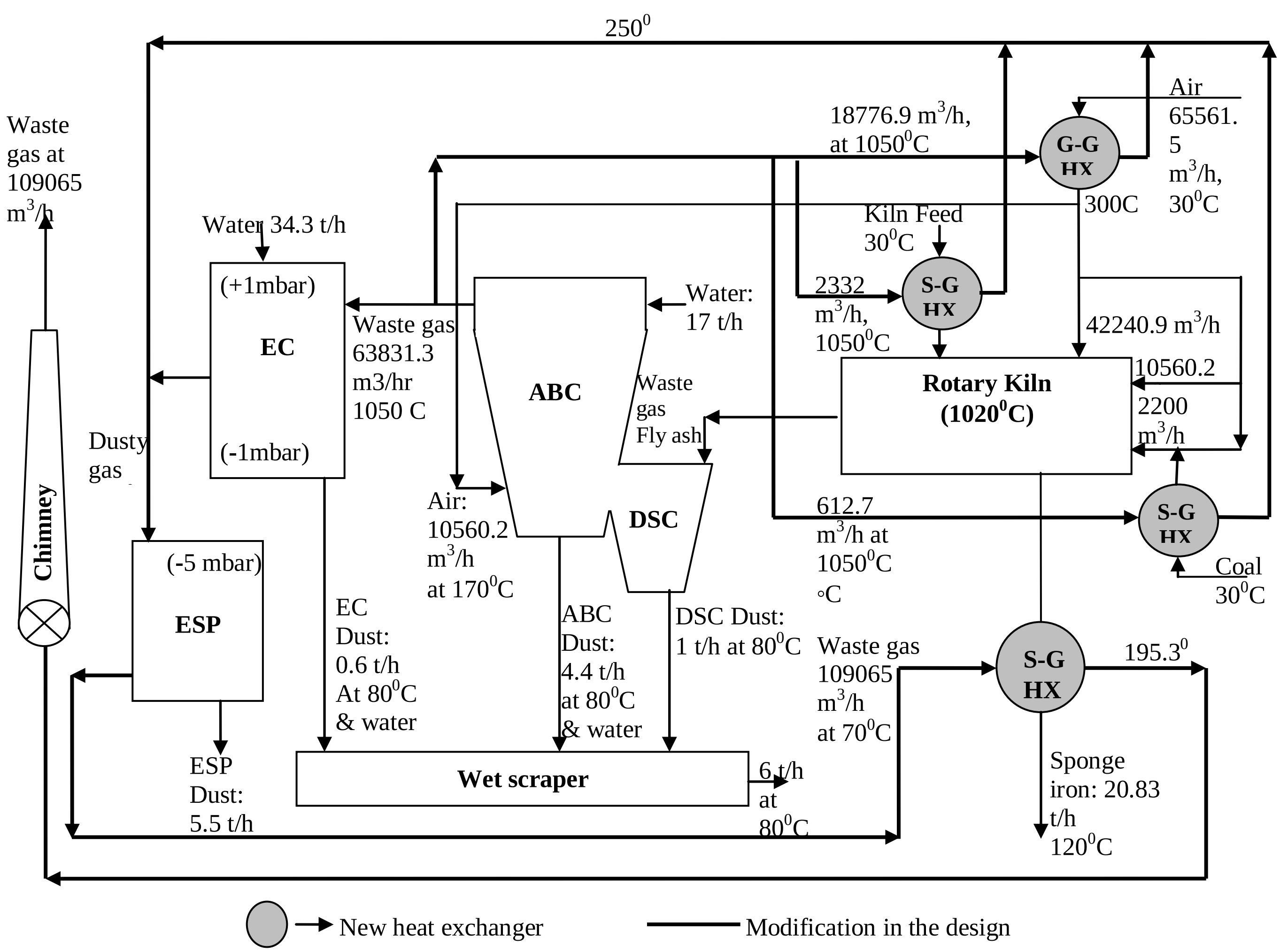

Figure 6. Process flow diagram for Case-4

5. CONCLUSIONS

It appears that during the operation, a tremendous amount of heat is produced and a significant part of this heat associated with the waste gas remains unutilized. If this useful heat content of waste gas is utilized then plant yield can be enhanced subsequently. The salient features of the present study are as follow:

1. Based on heat integration Case-4 is selected as best design amongst the four. It consumes 93.4% and 12.5% less water and coal in comparison to existing system. It gives total profit of Rs 1128602/day. However, to achieve this capital investment of Rs 62106561/- is required. Thus, total payback period is 56 days.
2. Further, it is seen that existing system consumes 5.57 times more energy than the theoretical value. This difference is reduced up to a value of 4.9 for Case-4 by heat integration in the process.

6. NOMENCLATURE

C	specific heat, J/kg◦C
D	diameter of kiln, m
G	gas
h	heat transfer coefficient, kJ/h m^2
L	length of kiln, m
m	mass flow rate, kg/h
Q	heat, kW
S	solid
T	temperature
t	tonne (=1000 kg)
NHV	net heating value, kJ/kg
CC	capital cost, Rupees
Subscript	
a	air
c	coal
m	moisture
p	process
hu	hot utility
s	ore, supply
t	target
r	radiation
loss	loss from kiln
i	inlet to kiln
Greek	
λ	latent heat of vaporization, kJ/kg

7. REFERENCES

1. B.B. Agrawal, K.K Prasad, S.B. Sarkar, H.S. Ray, Cold bonded ore-coal composite pellets for sponge ironmaking. Part 1 Laboratory scale development, *Ironmaking Steelmaking.* **27**, 421-425 (2000).
2. B.B. Agrawal, K.K Prasad, S.B. Sarkar, H.S. Ray, Cold bonded ore-coal composite pellets for sponge ironmaking. Part 2. Plant trials in rotary kiln, *Ironmaking Steelmaking.* **28**, 23-26 (2001).
3. S. Rani Devi, B. Mazumder, Recovery of carbon from sponge iron plants - studies on the dust samples, *Env. Sci. Eng.* **5**, 11-16 (2007).
4. H.P. Misra, B. Ipicol, Indian sponge iron production - problems and solutions. *SGAT Bulletin.* **7**, 37-46 (2006).
5. S.C. Jena, N.K. Patnaik, A. Sarangi, Heat and Mass Balance in Rotary Kiln Sponge Iron Making. *International Conference on Alternative Routes on Iron and Steel under Indian Conditions*, 3, 59-64 (1996).
6. A. Bandyopadhyay, A.K. Ray, M.P. Srivastava, S.V.B. Subbarao, K.K Prasad, P.K. Bandyopadhyay, R. Haque, B.R. Choudhary, Selection of Coals for Rotary Kiln Sponge Iron Plant. *Trans. Indian Inst. Metals.* **40**, 209-218 (1987).

7. G. Elsenheimer, H. Serbent, The current position of the SL/RN process taking into account conditions in India. *International Conference on Alternative Routes on Iron and Steel under Indian Conditions*, 2, 105-110 (1988).
8. H. Ebrahim, A. Ali, Thermal analysis of sponge iron preheating using waste energy of EAF. *J Mat. Proc. Tech.* **208**, 336-341 (2008).
9. D.K. Biswas, S.R. Asthana, V.G. Rau, Some Studies on Energy Savings in Sponge Iron Plants, *Trans. ASME*. **125**, 228-237 (2003).
10. K. Eriksson, M. Larsson, Energy survey of the Sponge Iron Process. www.chemeng.lth.se/exjobb/052.pdf. (2005).
11. D. Mignard, C.A. Pritchard, Review of the sponge iron process for the storage and transmission of remotely generated marine energy, *Int. J Hydrogen Energy*. **32**, 5039 – 5049 (2007).
12. Comprehensive industry document on sponge iron industry. http://www.cpcb.nic.in/upload/NewItems/NewItem_102_SPONGE_IRON.pdf (2007).
13. K.H. Ulrich, J.K. Tandon, The CODIR process for India – an example for optimum coal usage and its potential for energy recovery, *International Conference on Alternative Routes on Iron and Steel under Indian Conditions*, 2, 21-25 (1988).
14. A.K. Prasad, R.K. Prasad, S. Khanam, Design Modifications for Energy Conservation of Sponge Iron Plants. Journal of Thermal Science and Engineering Application, Manuscript No. TSEA-10-1030 (Submitted on 16.03.10).
15. B. Linnhoff, D.W. Townsend, D. Boland, G.F. Hewitt, B.E.S. Thomas, A.R. Guy, R.H. Marshal, "A user guide on process integration for the efficient use of energy", The Institution of Chemical Engineers, Rugby (1982).
16. D.W. Green, R.H. Perry, "Perry's Chemical Engineers' Handbook", McGraw-Hill (2008).
17. F. Grønvold, E.J. Sawelsen, Heat capacity and thermodynamic properties of α-Fe_2O_3 in the region 300-1050 K. Antiferromagnetic transition, *J Phy. Chem. Solids*. **36**, 249-256 (1975).
18. U.V. Shenoy, "Heat Exchange Network Synthesis: Process Optimization by Energy and Resource Analysis", Gulf Publishing Company, Tokyo (1995).
19. A.K. Prasad, R.K. Prasad, S. Khanam, Design of Duct for Sponge Iron Industry. Applied Thermal Engineering, Manuscript No. ATE-2009-306 (Submitted on 29.04.09).
20. R.K. Sinnott, "Chemical Engineering Design", Elsevier Butterworth-Heinemann (2005).