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Energy Efficiency Analysis of an Industrial Reheating Furnaces and Investigating Efficiency Enhancing Opportunities: Literature Review

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Abstract*— Steel is one of the most common materials come into contact in our daily life. Steel industry is one of the major industries for developing countries, and it is one of the industrial sectors that have the highest energy consumption. They are primary industry which serves material to secondary industry. Manufacturing industry has focused on increasing energy efficiency of their production process. Iron and steel industry always incorporates a reheating process in the production chain of their commodities. Reheating furnace is an essential facility of a rolling mill where a billet is heated to required rolling temperature. This paper discusses literature review about rolling process, purpose and need of reheating furnace and energy analysis of reheating furnaces

Index Terms— **Energy consumption, Reheating process.**

I. INTRODUCTION

Rolling is one of the most important industrial metal forming operations. Rolling is the plastic deformation of materials caused by compressive force applied through a set of rolls. The cross section of the work piece is reduced by the process. The material gets squeezed between a pair of rolls, as a result of which the thickness gets reduced and the length gets increased. In steel plants reheating furnaces are used in hot rolling mills to heat the steel stock. To temperatures of around 1200 deg C which is suitable for plastic deformation of steel and hence for rolling in the mill. The heat source for a reheating furnace originates from combustion of the fuel.

Reheating furnaces are the main commodity that consume large amount of energy in steel manuacturing industry.This present work include deep literature review about energy various things regarding reheating furnaces.

II. ROLLING PROCESS

Rolling is one of the most important industrial metal forming operations. Hot Rolling is employed for breaking the ingots down into wrought products such as into blooms and billets, which are subsequently rolled to other products like plates, sheets etc. Rolling is the plastic deformation of materials caused by compressive force applied through a set of rolls. The cross section of the work piece is reduced by the process. The material gets squeezed between a pair of rolls, as a result of which the thickness gets reduced and the length gets increased. Mostly, rolling is done at high temperature, called hot rolling because of requirement of large deformations. Hot rolling results in residual stress-free product. However, scaling is a major problem, due to which dimensional accuracy is not maintained. Cold rolling of sheets, foils etc are gaining importance, due to high accuracy and lack of oxide scaling. Cold rolling also strengthens the product due to work hardening.

Rolling mill consists of rolls, bearings to support the rolls, gear box, motor, speed control devices, hydraulic systems etc. The basic type of rolling mill is two high rolling mills. In this mill, two opposing rolls are used. The direction of rotation of the rolls can be changed in case of reversing mills, so that the work can be fed into the rolls from either direction. Such mills increase the productivity. Non reversing mills have rolls rotating in same direction. Therefore, the work piece cannot be fed from the other side. Typical roll diameters may be 1.4m. A three high rolling mill has three rolls. First rolling in one direction takes place along one direction. Next the work is reversed in direction and fed through the next pair of roll. This improves the productivity.

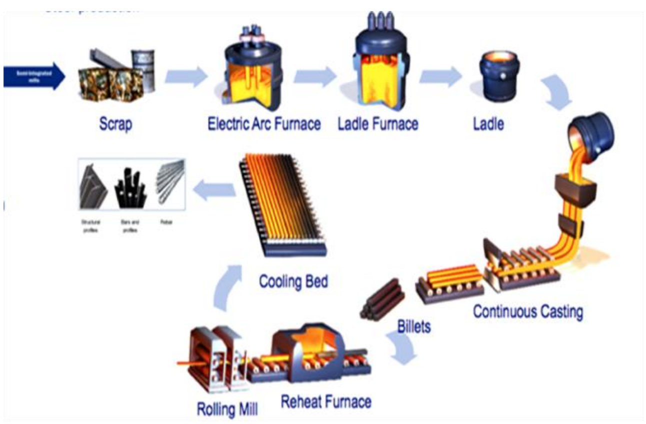

Fig 1: Line diagram of rolling process

III. REHEATING PROCESS

Reheating is a continuous process where the stock is charged at the furnace entrance, heated and discharged. Energy is transferred to the items during their traverse through

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the furnace by means of convection and radiation from the hot burner gases and the furnace walls. The Heating operation in the reheating furnaces is associated with combustion of fuel as mixed gas and preheated air, the generated heat exchanged from the combustion products to the walls of furnace and finally from the combustion products &the walls of furnace to the stock by conduction/convection/radiation processes. Combustion process and the process of heat transfer from the combustion products to the stock have some limitations and may create some quality problems in the final products. The oxidation of the steel during reheating cycles as function of entire furnace atmosphere like oxidizing or reducing, steel residence time in the furnace and steel temperature that causes scale formation and wastage of energy in terms of metal loss.

➢ ***Importance of reheating process***

In the reheating furnaces, the thermal efficiency and uniform heating play an important role in reduction of energy cost and minimization of metal defects. The purpose of a reheating furnace is to provide uniformly heated slabs/blooms/billets at the discharge end of the furnace before they are rolled. In steel plants reheating furnaces are used for hot rolling mills to heat the steel stock(billets , blooms or slabs) to temperature of around 1200 degree celcious which is suitable for plastic deformation of steel and hence for rolling in the mill.

➢ ***Purpose of reheating process***

Reheating furnaces constitute an important element of the rolling mills, in which the semi-finished steel products are heated to a desired temperature for achieving the plastic properties in the products for rolling. The basic Purposes of heating the semi-finished metal products for rolling, is to soften the metal suitable for rolling. Providing a sufficiently high initial temperature so that rolling process is completed in fully austenitic temperature region. In order to have smooth operation of rolling mills, design features and operation of reheating furnaces plays an important role. The design features and operating parameters determines the quality of rolled product, yield, energy consumption, pollution and the economics of the product. In modern walking beam reheating furnaces, semi-finished products such as slabs/blooms/billets are uniformly heated to a desired temperature and have minimized skid marks. The operations of walking beam reheating furnaces are computerized control (using PLC/DCS systems along with level 2 systems) to achieve higher energy efficiencies and to have plan view rolling.

IV. REHEATING FURNACE

In steel plants reheating furnaces are used in hot rolling mills to heat the steel stock, to temperatures of around 1200 deg C which is suitable for plastic deformation of steel and hence for rolling in the mill. The heat source for a reheating furnace originates from combustion of the fuel. A complete combustion takes place when there is the proper ratio between oxygen and fuel, namely a stoichiometric combustion, is provided. . The heating process in a reheating furnace is a continuous process where the steel stock is charged at the furnace entrance, heated in the furnace and discharge at the furnace exit. Heat is transferred to the steel stock during its traverse through the furnace mainly by means of convection and radiation from the burner gases and the furnace walls. The charging temperature of the steel stock may range from ambient temperature to 800 deg C. The target exit temperature of the steel stock is governed by the requirement of the process of rolling which is dependent on the rolling speed, stock dimension and steel composition. Steel quality aspects put constraints on temperature gradient and surface temperature. Fuel used in these furnaces can be liquid or gaseous fuel.

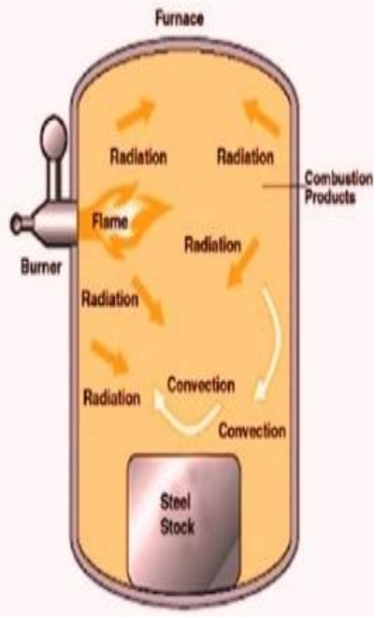

Fig 2: Reheating Furnace

➢ ***Main features of reheating furnace***

The size of reheating furnace is usually expressed as the capacity to supply the rolling mill with sufficiently hot steel from the cold stock and is expressed in tons per hour. The energy efficiency of reheating furnace is usually defined as increase of steel stock heat content when heated from 10 deg C to 1200 deg C divided by the fuel energy (latent heat plus sensible heat) used for it. Many design features of the furnace affects the energy efficiency. These includes i) type of burners ii) Furnace dimensions iii) Number of furnace zones iv) type of wall and roof insulation v) skid design and vi) preheating of fuel and combustion air in recuperators by the hot flue gases coming out from the furnace exit.

The parameters important for furnace design includes i) the quantity of heat to be imparted to the charge, ii) generation of sufficient heat within the furnace to heat the steel stock and overcome all steel losses, iii) transfer of generated heat to the surface of the steel stock to be heated, iv) equalization of temperature within the steel stock and v) reduction of heat losses from the furnace to the minimum. Operational practices are also important for the energy efficiency.

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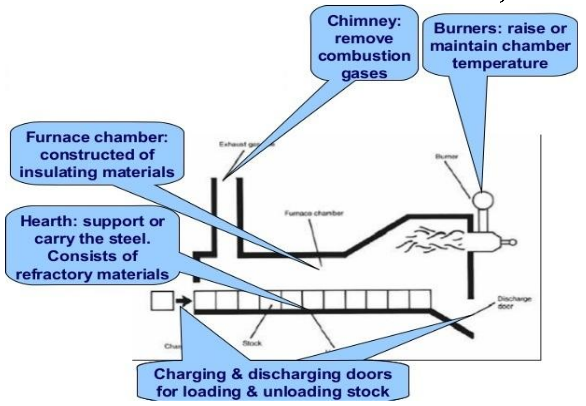

Fig 3: Components of Reheating Furnace

➢ ***Zones of reheating furnace***

Typical reheating furnace has 3 zones. Preheating, heating and soaking zone. Preheat zone heats the billet for moisture removing in the temperature range from 750 to 850 degree celcious. The heating zone provides heat to the billet in the temperature range 950-1150 degree celcious& soaking zone temperature in the range from 1000-1100 degree celcious. The furnace is divided into three zones, two reheating zones and a soaking zone, which is again divided into three control zones in order to create temperature difference along the billet. Low sulphur heavy fuel oil is used as a burning fuel. The regenerative burners are situated in the beginning of the 1st heating zone. The pre-heating zone, heating and soaking zones are top fired with six burners per zone. The flue gases go through a recuperator. The main limitation in increasing the capacity was the combustion air temperature coming through the recuperator.

Fig 4: Zones of Reheating Furnace

➢ ***Classification of reheating furnace***

The reheating furnace classification can be done in several ways. These are described below.

1. Based on the method of heating a reheating furnace can be combustion type or electric type. The combustion type furnace can be oil fired or gas fired.

2. Based on method of charging reheating furnaces can be classified as batch type or continuous type..

3. Continuous furnaces can be further classified based on the movement of steel stock inside the furnace. Based on this classification the continuous type reheating furnaces are pusher type, rotary hearth type, walking beam type, walking hearth type or roller hearth type.

4. Based on heat recovery, the reheating furnace can be either regenerative or recuperative. Presently only recuperative type of reheating furnaces are in use.

Batch Furnace: These are the older type of furnaces which are capable of heating all grades and sizes of steel. The steel stock to be heated in this type of furnace is charged and drawn through front doors by a charging machine. These furnaces vary in size ranging from hearths of less than a square meter with a single access door to those with hearths of around 6 m in depth and around 15 m in length and with 5-6 numbers of access doors. Batch furnaces can be operated to heat materials to temperatures around 1320 deg C more satisfactorily than a continuous furnace. They can also be used as a reservoir for holding hot material directly from the primary mill for later rolling in the finishing mill.

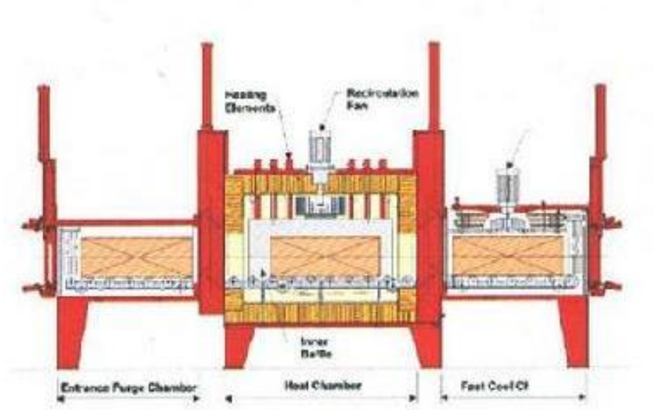

Fig 5: Batch Furnace

Continuous pusher furnace: In this type of furnace cold steel stock is pushed forward with the help of pushers at the charging side. Earlier these furnaces were designed for heating billets or smaller sections of blooms. The hearth of earlier furnaces was short in length and sloped downward longitudinally towards the discharge end in order to permit easy passage of steel stock through the furnace. Presently pusher furnaces are longer with hearths of around 25- 30 m length. These furnaces are with top and bottom firing and equipped with preheating, heating and soaking zones. Multiple zone furnaces such as five zone slab reheating furnace have also been designed and operated. Cold steel stock can be charged in such furnace either from the end or through a side door. In either case the steel stock is moved forward by pushing the last piece charged with a pusher at the charging end. With each pushing of the cold steel stock against the continuous line of material, a heated piece is discharged at the discharge end by gravity either through an end door upon a roller table feeding the rolling mill, or pushed

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through a side door to the mill roller table by suitable manual or mechanical means or withdrawn through the end door by a mechanical extractor. Lower temperature differences between two pieces of material pushed.

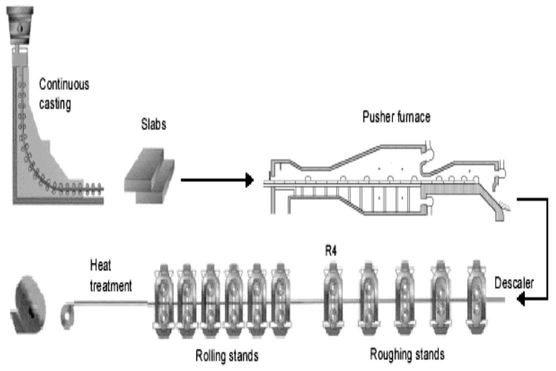

Fig 6: Continuous Casting Furnace

Rotary hearth furnace: A rotary hearth furnace is used for heating round billets in pipe plants and for heating short length blooms or billets in a forging plant. In the rotary hearth furnace the external walls and roof remain stationary while the hearth section of the furnace rotates. Rotary hearth furnace eliminates the manual labor needed for rolling round billets forward on horizontal or moderately sloped hearth and the disadvantage of excessively sloped hearth in a continuous furnace. This furnace has better means of controlling the rate of heating at all temperature levels when compared with a batch type furnace.

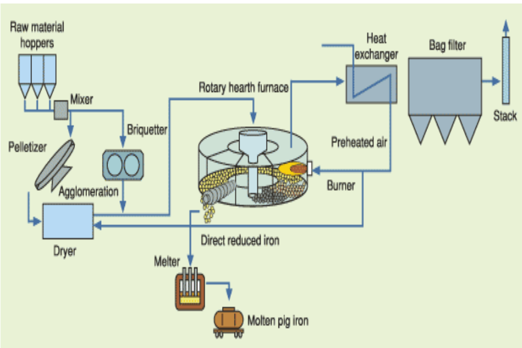

Fig 7: Line Diagram of Rotary Hearth Furnace

***Walking beam furnaces*:** Initially walking beam furnaces were designed with alloy steel walking beams which were exposed directly to the furnace heat and were also subjected to heat corrosion. Hence these furnaces were operated at maximum temperatures of 1065ºC. These furnaces were not suitable for heating steels where the temperature of reheat is up to 1320ºC.Presently the walking beam is made of water cooled steel members lined with refractories so that only the refractories are exposed to the heat of the furnace. Alternatively, the beams and supports are constructed of water cooled pipe sections with buttons on the top surfaces to keep away the hot material from direct contact with the water cooled pipes. Walking beam furnaces are now used to reheat billets, blooms and slabs. Walking beam furnaces are usually designed with end or side charging and discharging. The beams can be actuated either hydraulically or mechanically. Cross firing with side wall burners above and below the material stock being heated are being used. In some furnaces the material is heated with radiant type roof burners or with burners placed in the roof and below the material. It is feasible to empty the furnace from either side by activating the beam mechanisms.

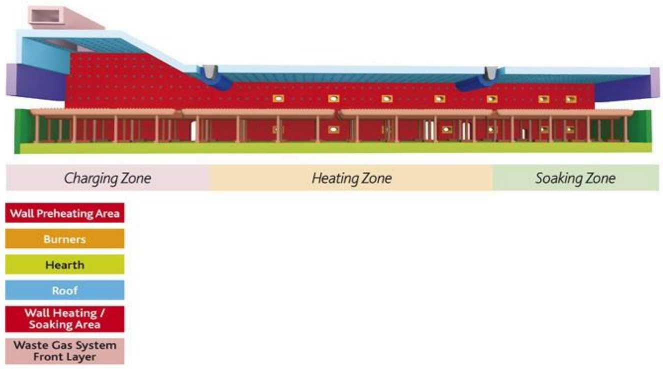

Fig 8: Walking Beam Furnace

Walking hearth furnaces: It is similar to the walking beam furnace when passage of steel stock through the heating chamber is considered. The difference in method of conveyance in these two furnaces is that in the walking hearth furnace the steel stock rests on fixed refractory piers. These piers extend through openings in the hearth and their tops are above the hearth surface during the time when the material is stationary in the furnace. The furnace gases can thus circulate between most of the bottom surface of the work and the hearth. For movement of the material toward the discharge end of the furnace, the hearth is raised vertically to first contact the material and then raised further for a short distance above the piers. The hearth then moves forward a preset distance, stops, lowers the material on to its new position on the piers, continues to descend to its lowest position and then moves backward to its starting position toward the charging end of the furnace to await the next stroke. The advantages and disadvantages of a walking hearth furnace are similar to those of a walking beam furnace.

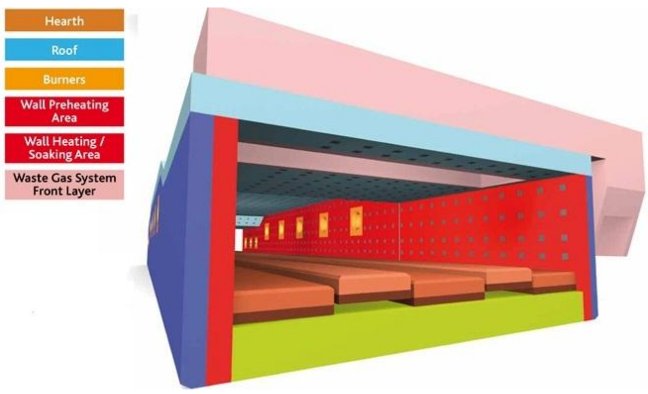

Fig 9: Walking Hearth Furnace

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Roller hearth reheating furnaces: Roller hearth furnaces are used to advantage when heating very long billet, bloom or slabs in the situation where it is not practical for heating in a pusher or walking beam furnace. The advantages of the roller hearth reheating furnaces are:

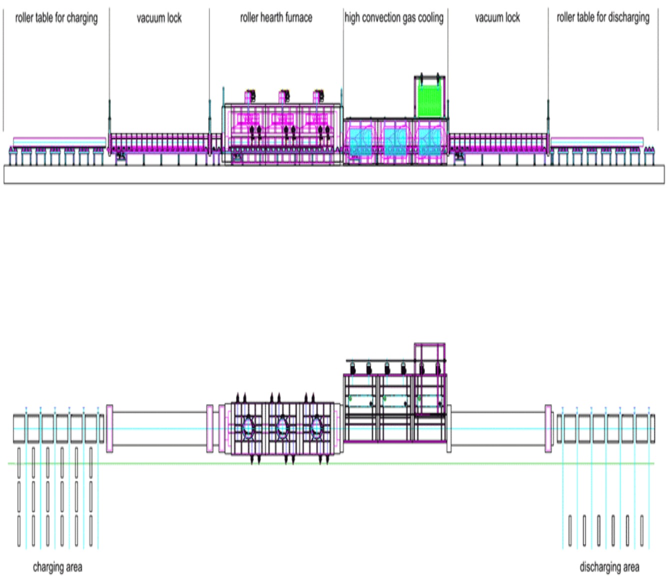

Fig 10: Line Diagram of Roller Hearth Furnace

V. BURNER

The important parameters for a reheating furnace include the burners and their location for proper heat distribution. Burners used in the reheating furnaces constitute one of the important aspects which decide the energy efficiency of the reheating furnace Hence for the proper heat distribution inside the furnace, it is important that the burners should have flexibility so that the operating personnel can adapt the combustion parameters to suit the diverse process conditions. The arrangement of burners in a reheating furnace is also very important for heating characteristics of the furnace. According to the position of the burners in the furnace, arrangements are classified into three heating methods namely (i) Use of axial-flow burners in front wall, (ii) use of side burners in side walls, and (ii) Use of flat flame radiant burners in the roof.

- ***Classification of burners;***

Flat flame Burner: The flat flame burners (FFB) are usually used on the roof of the reheating furnace. Due to these burners indirectly oriented radiant heat transfer takes place. The heat from fuel combustion is transferred to the steel charge material not only directly from the flame, but also through the roof refractory lining of the furnace. The flame, which is normally non-luminous, is characterized by high temperature and relatively low emissivity corresponding to selective radiation of carbon dioxide and water vapour. For lack of flame impact on the steel charge material the FFB heated furnaces are known as indirect heating furnaces.

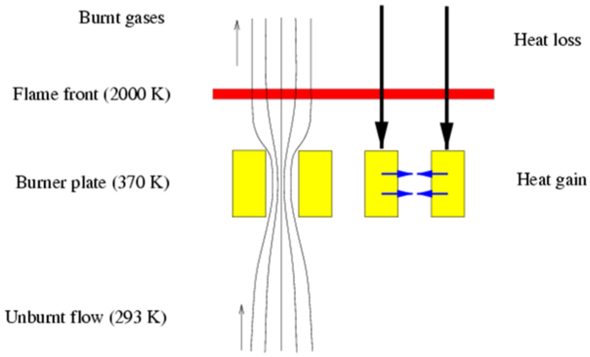

Fig 11: Flat Flame Burner

Long flame burners: A large variety of long flame burners of various characteristics and different capacities are available in the market. These burners are available in various capacities and to suit use of different fuels such as oil, gas or multiple fuels. In the reheating furnace with the long flame burners, since the major part of the heating of the steel charge material takes place by convection, the re-circulation of products of combustion substantially contributes to the speed of heating and temperature uniformity. Long flame burners produce high velocity gases which entrain and re circulate the combustion gases to achieve temperature uniformity in the furnace with minimum of excess air. The burners at the front wall of the reheating furnace are usually of longer flame while those at the side wall of the furnace are of shorter variable flame. The burners at the front wall of the reheating furnace are normally of axial flow burning type and need wide range of adjustment. They are large capacity burners and have limitation of the length per zone in the direction of the furnace length. The flow of burning gases inside the furnace is smooth along the furnace length. The nose parts of the burners make the structure of the furnace complicated. With these burners there is uniformity of heating along the furnace width but the temperature tends to fall at the nose parts in the direction of furnace length. The workability is relatively good except around burners at lower area where the temperature is relatively high.

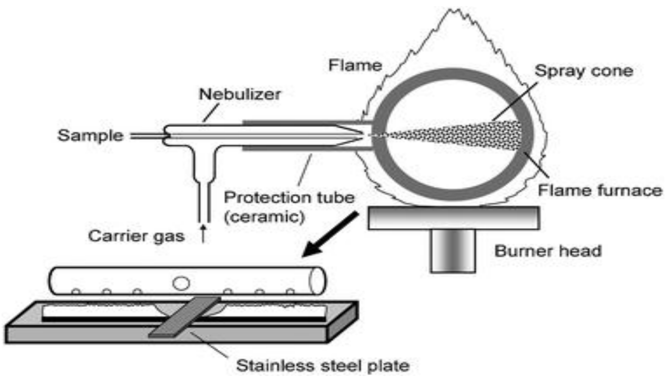

Fig 12: long Flame Burner

Regenerative and recuperative burners: A regenerative burner is with a heat recovery system that recovers the waste heat of the furnace exhaust gas to heat up the combustion air needed for the burning of the fuel at the burner. Use of

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regenerative burners for reheating furnaces can provide significant energy savings. The regenerative burners are designed to recover the heat to the inlet air by transferring the heat from the exhaust gas to the inlet air which is to be used in the combustion. The regenerative burner has two set of burners each with a regenerator and the reversing valve. The regenerator uses the ceramic (usually alumina) balls to collect the heat. While the first regenerative burner is firing, the other is exhausting the furnace gases. The exhaust gas is passed through the regenerative burner body and transfers the heat to the ceramic balls. Hence, the heat from exhaust gas is transferred to the inlet air since it is passed through the heated ceramic balls. The reversing valve sets the direction of the air flow that enters into the burner head, which makes the inlet air temperature similar to the operating temperature. Due to a high preheat combustion air temperature, the regenerative burner can save the fuel and make the combustion with high efficiency. In case of a recuperative burner, the structure of the burner is the similar to the radiation heat exchanger tube which heats the inlet air up to the higher temperature (about 750 deg C) by recovering the heat from the exhaust gas to the inlet air. Hence, the exchanged heat in the burner can improve the combustion efficiency and save the fuel cost approximately 25 % to 30 %.

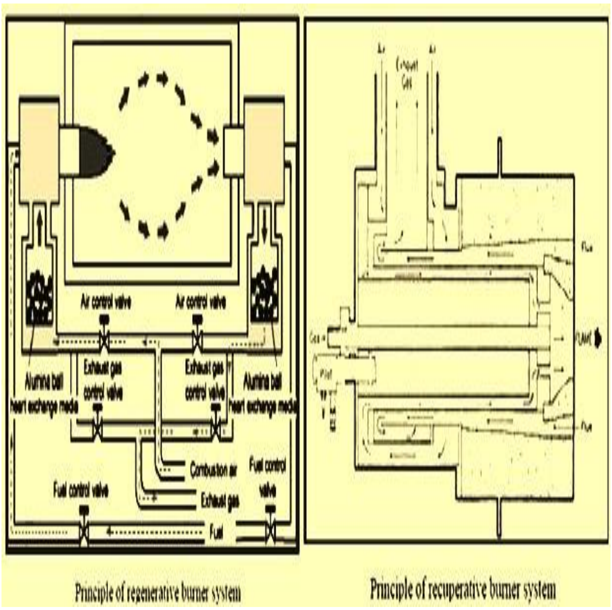

Fig 13: Principle of Regenerative and Recuperative Burner

Oxy fuel burners: Oxy fuel refers to the practice of totally replacing air as the source of oxidizer for combustion with industrial grade oxygen. Oxy fuel combustion reduces or eliminates nitrogen in combustion air and substantially reduces waste heat carried out with flue gas. The oxy fuel burners can be used in high temperature reheating furnaces where temperature uniformity is critical and extremely low NOx emissions are desired.

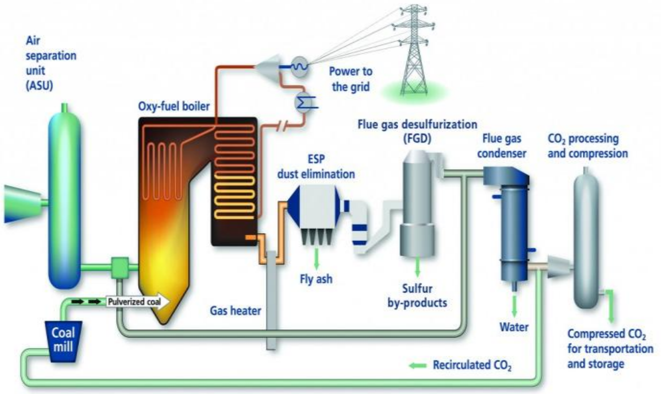

Fig 14: Oxy Flame Burner

VI. THERMAL ENERGY ANALYSIS OF REHEATING FURNACE

➢ ***Furnace Efficiency***

The efficiency of a furnace is the ratio of useful output to heat input the furnace efficiency can be determined by both direct and indirect method.

1. Direct Method
2. Indirect Method

Direct method: 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 formulae.

Thermal efficiency of the furnace = *(Heat in the Stock)/ (Heat in the Fuel Consumed)*

$$Q = m \times Cp\,(t_2 - t_1)$$

Where, Q=quantity of heat in kcal

m=Weight of the material in kg

Cp=Mean specific heat kcal/kg°c

t_2=Final temperature desired, °c

t_1=initial temperature of the charge before it enter furnace °c

Indirect method: Furnace efficiency is calculated after subtracting sensible heat loss in flue gas, loss due to moisture in flue gas, heat loss due to opening in furnace, Heat loss through furnace skin and other unaccounted losses from the input to furnace. In order to find out furnace efficiency using indirect method, various parameters that are required are hourly furnace oil consumption, material output, excess air quantity, temperature of flue gas, temperature of furnace at various zones, skin temperature and hot combustion air temperature. Efficiency is determined by subtracting all the heat losses from 100.

Measurement parameters: The following measurements are to be made for doing the energy balance in oil fired reheating furnaces (e.g. Heating Furnace)

i) Weight of stock / Number of billets heated

ii) Temperature of furnace walls, roof etc

iii) Flue gas temperature
iv) Flue gas analysis
v) Fuel Oil consumption

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

Losses in reheating furnace

1. Loss due to evaporation of moisture present in fuel
2. Loss due to evaporation of water formed due to hydrogen fuel
3. Sensible heat loss in flue gas
4. Heat loss due to opening
5. Heat loss through skin
6. Unaccounted loss

➢ *Sensible Heat Loss in Flue Gas:*

Excess air = $O_2/(21-O_2)*100$

Where O2 is the % of oxygen in flue gas

Sensible heat loss = $m \times C_p \times \Delta T$

M=weight of flue gas

Actual mass of air supplied / kg of Fuel + mass of fuel (1kg)

Cp=specific heat of flue gas

ΔT=temperature difference

➢ *Loss due to evaporation of moisture present in fuel*

% of loss=M {584+0.45(Tfg-Tamb)}*100/GCV of Fuel

M = KgOf Moisture in 1 Kg of Fuel Oil

T_{fg}= Fuel Gas Temperature

T_{amb}= Ambient Temperature

GCV = Gross Calorific Value of Fuel

➢ *Loss due to evaporation of water formed due to hydrogen fuel:*

% of loss = 9*H2 {584+0.45(Tfg-Tamb)}*100/1000

Where, H2 = kg of H2 in 1 kg of fuel oil

➢ *Heat Loss Through Skin*:

Method 1: Radiation Heat Loss from Surface of Furnace

$$Q = a \times (t_1 - t_2)^{5/4} + 4.88E\left[\left(\frac{t_1+273}{100}\right)^4 - \left(\frac{t_2+273}{100}\right)^4\right]$$

where

Q: Quantity of heat release in kCal / W / m^2

a : factor regarding direction of the surface of natural convection ceiling = 2.8, side walls = 2.2, hearth = 1.5

t_1 : temperature of external wall surface of the furnace (°C)

t_2 : temperature of air around the furnace (°C)

E: emissivity of external wall surface of the furnace

Method 2 : Radiation Heat Loss from Surface of Furnace

The following Figure 15 shows the relation between the temperature of external wall surface and the quantity of heat release calculated with this formula.

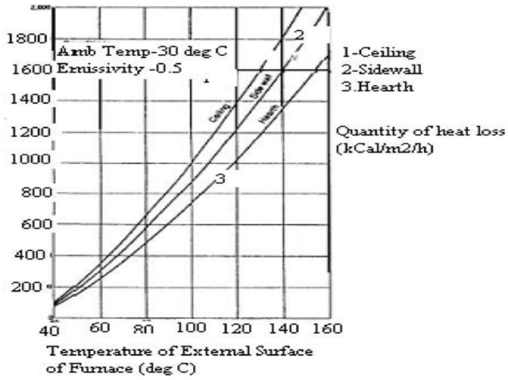

Fig 15: Quantity of Heat Release at Various Temperatures

➢ ***Heat Loss due to Openings:***

If a furnace body has an opening on it, the heat in the furnace escapes to the outside as radiant heat. Heat loss due to openings can be calculated by computing black body radiation at furnace temperature, and multiplying these values with emissivity (usually 0.8 for furnace brick work), and the factor of radiation through openings. Factor for radiation through openings can be determined with the help of graph as shown in figure 16. The black body radiation lossescan be directly computed from the curves as given in the figure 17

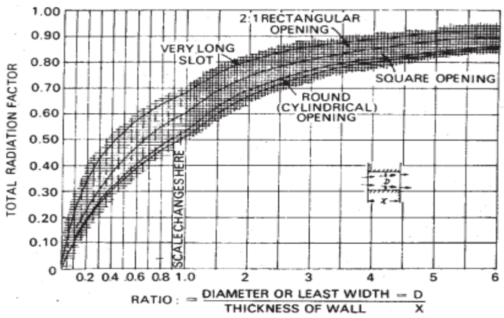

Fig 16: Factor for Determining the Equivalent of Heat Release from Openings to the Quality of Heat Release from Perfect Black Body

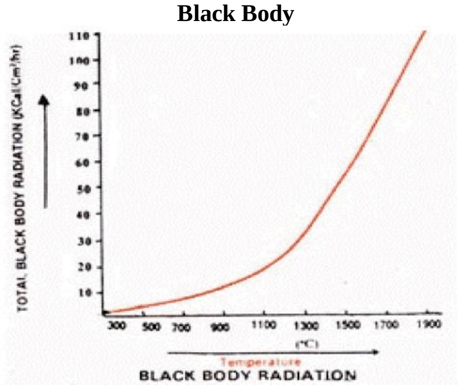

Fig 17: Graph for Determining Black Body Radiation at a Particular Temperature

➢ ***Unaccounted Loss***

These losses comprise of heat storage loss, loss of furnace gases around charging door and opening, heat loss by incomplete combustion, loss of heat by conduction through hearth, loss due to formation of scales.

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Furnace Efficiency (indirect method) =100-(Sensible heat loss in flue gas+ Loss due to evaporation of moisture in fuel+ Loss due to evaporation of water formed from H2 in fuel+ Heat loss due to openings+ Heat loss through skin)

VII. CONCLUSION

Reheating furnace are the important component in steel manufacturing industry75% of the total energy is consumed by the reheating furnace Optimizing energy utilization of reheating furnace increases economic efficiency of industry

VIII. FUTURE WORK

Conducting energy analysis of reheating furnace in the steel manufacturing industry identifies the thermal efficiency of reheating furnace. Study has to be conducted in order to identify any opportunities for increasing efficiency of furnace with less cost .There by energy consumption in the steel manufacturing industry can be reduced in future.

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