RECUPERATOR DESIGN FOR INDUSTRIAL REHEATING FURNACE

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I certify that the thesis is submitted by Selcuk SELIMLI titled as ''RECUPERATOR DESIGN FOR INDUSTRIAL REHEATING FURNACE'' is fully adequate in scope and quality as a thesis for the degree of Master of Science.

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“All the information in this thesis has been obtained in accordance with academic rules and ethical principles, and offered, and also derived from this study as required by these rules and principles, I declare that I did all of the citations.”

Selcuk SELIMLI

ABSTRACT

M.Sc. Thesis

RECUPERATOR DESIGN FOR INDUSTRIAL REHEATING FURNACE

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Nowadays, increase of energy demand and costs, lack of energy resources, competitive conditions in the market and environmental considerations require the efficient usage of energy. In this context, an industrial facility rail profile mill reheating furnace fuel optimization, a new recuperator which is highly corrosion resistant against the corrosive effect of flue gases, high heat transfer capacity design, production and assembly has been carried out to increase the heat transfer from the high temperature (700~850^{o}C) furnace flue gas to the furnace combustion air to ensure maximum efficiency. While existing recuperator design was providing about 375°C combustion air from 820°C flue gas, new recuperator design has been providing about 575°C combustion air from 820°C flue gas. Thus, the energy saving and emission reduction have been ensured, and also high quality product and low cost production has been obtained.

Keywords : Energy analysis, energy efficiency, recuperator, waste heat recovery, reheating furnace.

Scientific Code : 914.1.038

ÖZET

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Günümüzde, enerji ihtiyacı ve maliyetlerinin artması, enerji kaynaklarının kısıtlılığı, piyasadaki rekabetçi koşullar ve çevresel duyarlılık enerji kaynaklarının verimli kullanımını gerektirmektedir. Bu bağlamda, bir özel kuruluşun ray profil haddehanesi tav fırınında, yakıt optimizasyonu ve yüksek enerjili (700-850^{o}C) fırın egzoz gazından fırın yakma havasına ısı aktarımını artırarak maksimum düzeyde verim sağlamak üzere baca gazının korozitif etkisine dayanıklı, yüksek ısı transferi kapasiteli yeni bir reküperatörün tasarlanması, imalat ve montajının yapılması sağlanmıştır. Eski reküperatör de, baca gazı sıcaklığı 820°C için yakma havası sıcaklığı 375°C elde edilirken, yeni tasarlanan reküperatör 820^{o}C baca gazı sıcaklığı için 575°C yakma havası sağlamaktadır. Bu sayede enerji geri kazanımı ve emisyon azalımı sağlanırken, ayrıca yüksek kaliteli ürün ve düşük maliyetli üretim elde edilmiştir.

Anahtar Sözcükler : Enerji analizi, enerji verimliliği, reküperatör, atık ısı kazanımı, tavlama fırını.

Bilim Kodu : 914.1.038

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SYMBOLS AND ABBREVIATIONS INDEX

SYMBOLS

$\dot{m}_b$: Mass flow rate of bloom

c_p : Specific heat capacity

Q_b : Heat applied to bloom

Q_f : Fuel mixture heating value

c_{p_a} : Specific heat capacity of air

c_{p_f} : Specific heat capacity of flue gas

$\dot{m}_a$: Mass flow rate of air

$\dot{m}_f$: Mass flow rate of flue gas

ΔT_m : Logarithmic mean temperature

U : Overall heat transfer coefficient

k_{ow} : Thermal conductivity of wall

h_{rg} : Radiation heat transfer coefficient of flue gas

h_c : Pure convection heat transfer coefficient

G : Mass velocity of gas

D : Tube diameter

ABBREVIATIONS

ERW : Electrical resistance welding

PART 1

INTRODUCTION

Today, the big proportion of energy is obtained from consumable energy resources such as fossil fuels and these fuels are obtained by import. Increasing energy demand has become dominant factor on the economy of the countries and the development of the industry. Countries suffer from energy crisis. Energy demand of industry is increasing parallel by the development of technology and increasing production rates. There is a big competition about quality and cost in the market. The optimum quality and minimum cost directly depend on energy usage. Efficient usage of energy cares the minimum energy input and maximum usable energy output.

Steel production industry is the most intensive energy using sector in the industrial field. Energy demand of steel industry in the general energy demand of Turkey is about 6% and the percentage of this demand in industrial usage is about 15% [1].

Global warming and environmental considerations bring up another important point of efficient usage of energy to reduce undesired greenhouse gases. The energy consumption and GHG emissions by the iron and steel industry accounts for a large percentage, about 7.86 %, of the total GHG emissions in this district. In most countries the increased (or decreased) production was the main contributor to changes in CO2 emissions, while energy-efficiency was the main factor reducing emission intensities of steel production in almost all countries [2-3]. In this respect, the most effective and cheapest way is, to damp the possible energy crises, and reduce GHG, obtaining energy from waste heat and reuse the big proportion of this energy potential.

Energy consumption and steel production rates between 2000 and 2009 for the integrated facilities and approximations until 2020 are given in Table 1.1 [1].

Table 1.1. Energy consumption and steel production values between 2000 and 2009 [1].

	2000	2007	2008	2009	2010	2015	2020
Steel Production (tone/year)	5229	6392	7178	7562	9000	12000	15000
Energy Consumption (MJ/tone)	28646	22093	21516	21478	20971	19887	19468

Between 2000 and 2009 steel production rates increased total 45%, for per year about 5%, and energy consumption decreased total 25%, for per year about 2.7%. Energy consumption rates for per ton steel production in a steel production plant is given in Figure 1.1 [1].

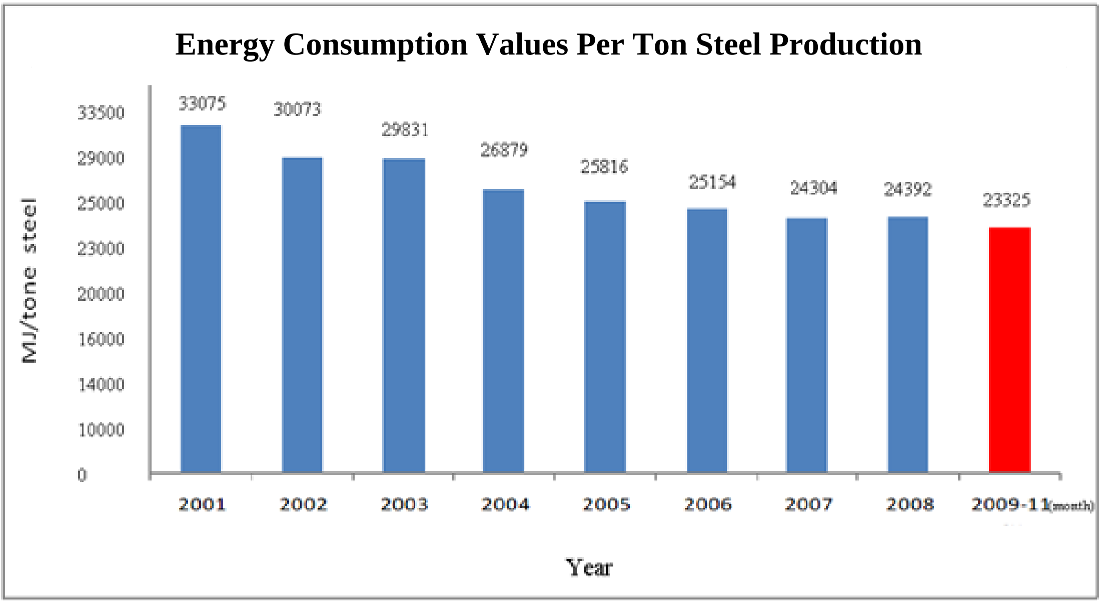


Figure 1.1. Energy consumption rates for per ton steel production in steel production plant [1].

High level of energy is used to melt metals and reheat products for forging. Especially blast furnaces and reheating furnaces are high energy intense regions at a steel production plant. High proportion of energy lost in these regions without energy saving efforts. Today about 26% of industrial energy is released to environment by the flue gas or liquid form [4]. This energy potential could be recovered by the true heat recovery system design and optimization.

In this thesis; energy consumption and performance of a rail profile mill reheating furnace was analysed. Getting energy from the waste heat and alternative recovery equipment were presented. Reheating furnaces, energy efficiency parameters and waste heat recovery from flue gas were estimated. The rail profile mill reheating furnace was examined, saving potential was identified. A new highly efficient high corrosion resistant, optimum cost recuperator design, production, assembly and optimization processes were occurred by the supports of Scientific and Technological Research Council of Turkey (TUBITAK) within the 1501 Industrial R&D AGY300-03 project. Energy efficiency of the reheating furnace has been increased by maximum heat recovery in the recuperator and minimum air leakages.

PART 2

LITERATURE STUDY

This chapter is the backbone of asserts about the improvement approximations of the system. Studies, are given below, support theoretically and experimentally this thesis and efficiency improvement studies on the system.

Ward et al. showed how the thermal efficiency and productivity of a forge furnace can be increased by using a high-temperature metallic recuperator for heat recuperation. Combustion air preheat temperatures up to 700°F (370°C) were achieved. The fuel consumption was reduced by 28% compared to the base case without heat recuperation. The heating time was reduced by 8% and scale formation on the outside of the billets was reduced by one third [5].

Chen et al. expressed that the furnaces are treated as a system; the measurements reveal that near 80% of heat in the furnaces is contributed by fuel combustion and 15.7% by hot flue gas. It follows that energy recovery via heat exchanger plays an important role in energy management. Furthermore, the practical measurements suggest that the efficiencies of heat exchange and heat recovery in the recuperating zone are 86.66% and 47.76%, respectively [6].

Minxing et al. determined that the overall efficiency in the reheat furnace is 60%. Flue gas losses are the biggest energy losses in the reheat furnace, accounting for 29.5% of the total energy losses during full production. Heat losses from wall, hearth and roof are also significant, being 7.139.170 kJ/h during full production. To reduce energy inefficiencies, it is recommended that billets be preheated to 315 °C in the reheat furnace. This requires 1.48 h to capture waste heat with a preheating section length of 1691.64 cm. The annual energy savings are estimated to be $215.086, 12 requiring a 3.03 years payback period [7].

Ho et al. showed that the specific energy consumption is 1095 kWh/t of rolled steel. The electric arc furnaces and the reheat furnaces are the major energy consumers, having specific energy consumption of 502 and 342 kWh/t; their thermal efficiencies are 50 and 62%, respectively. Scrap preheating of the third charge, optimizing the reheat furnace production rates, and recovery of furnace waste heat to preheat fuel oil offer potential for substantial energy savings [8].

Aljundi estimated that the percentage ratio of the exergy destruction to the total exergy destruction was found to be maximum in the boiler system (77%) followed by the turbine (13%), and then the forced draft fan condenser (9%). In addition, the calculated thermal efficiency based on the lower heating value of fuel was 26% while the exergy efficiency of the power cycle was 25%. Chemical reaction is the most significant source of exergy destruction in a boiler system which can be reduced by preheating the combustion air and reducing the air–fuel ratio [9].

Rhine and Tucker estimated that continues furnaces achieve efficiencies of over 60%, a remarkable value considering that there is no external heat recovery system [10].

Rasul et al. showed that the burning efficiency and the second law efficiency of a kiln system are 52.07% and 57.07% respectively. Cooler efficiency and heat recovery efficiency are 47.75% and 51.2% respectively. The unaccounted loss at kiln system was found to be 1.85% and that of cooler system was 19%. Irreversibility of the system was found to be about 20%, which is due to the conversion from chemical to thermal energy. This study show that by replacing industrial diesel oil (IDO) with waste heat recovery from kiln and cooler exhaust for drying of raw meal and fuel, and preheating of combustion air, a cement industrial facility can save about 1.264×10^5 US dollars per year [11].

Monteiro and Mello have used the CFD simulations with success in the study and development of heat exchangers. One great advantage of this technique is that it turns possible the evaluation of details of the flow and heat transfer inside the equipment. Consequently, it permits the improvement of one preliminary design of heat exchanger before prototype manufacturing and testing [12].

Bhattacharyya et al. attempted to unravel the exact reasons for premature failure of stainless steel tubes inside a recuperator used for preheating air for combustion inside a slab-reheating furnace of a Hot Strip Mill. Analysis suggests that the tubes failed due to sulphidation. Suitable materials have been recommended which could exhibit superior life and measures to minimize the adverse effects of the environment at the operating temperature. The tubes failed by sulphidation. The atmosphere inside the recuperator is expected to be oxidizing, minor increase in H_2S levels has significant influence on the corrosion pattern. If H_2S is below 50 ppm with oxygen around 5% in exhaust gas, use of 12% Cr–1% Mo (similar to AISI 416) stainless steel should impart adequate life. The life of the tubes can be further enhanced by using AISI 446 (25% Cr). If H_2S contents in the atmosphere are higher and oxygen levels lower than 1%, then any of the stainless steel in AISI series would corrode very fast. In such situations use of simple 18-8 stainless steel (AISI 304) is recommended [13].

Seong et al. attempted to evaluate the corrosion resistance of possible protective coatings for recuperators, nickel- and cobalt-based self-fluxing alloys, iron-based alloys, and chromium carbide cermet coatings were tested. The coatings with high chromium content, either as a form of carbide or as an alloying element, had excellent corrosion resistance. A Cr,C,-NiCr coating in carbide form, and Ni-45Cr-4Ti as an alloy coating can be recommended as promising coatings for the heat exchanger pipes, even in cases where they may encounter molten salt corrosion attack [14].

Hasanuzzaman et al. reviewed the energy efficiency and savings strategies in the combustion based industrial process heating. By using recuperator up to 25% energy can be saved in the furnace. In the case of boiler, by using economizers 10% to 20% energy can be saved. Economic analysis shows that the payback period of recuperator and economizer are normally less than 2 years. It is also found that the payback period is lower when operating hour is comparatively high [15].

Chawla discussed about newly developed heat exchanger THERMOWIR. A total of 11 MWe can be generated from 220.000 Nm3 h^{-1} flue gases at 600°C being cooled to 150°C. High electric power generation with low extra cost of fuel is the result. The cost of cement production can be reduced by approx. 10% [16].

Fath and Hashem presented a waste heat recovery scheme for the Dura (Baghdad, Iraq) oil refinery energy plant. Both the wasted heat of the process return condensate and the flue gases are utilized for low temperature feed-water and fuel heating. The steam saved, both from the main steam line and turbine extraction system, was found to increase the steam and plant overall efficiency by 18% [17].

Noie-Baghban and Majideian discussed about an air-to-air heat pipe heat exchanger design, construction and test under low temperature (15–55°C) operating conditions, using methanol as the working fluid. Experimental results for absorbed heat by the evaporator section are very close to the heat transfer rate obtained from computer simulation. Considering the fact that this is one of the first practical applications of heat pipe heat exchangers, it has given informative results and paved the way for further research [18].

Wang et al. discussed about the membrane based TMC technology was originally developed, demonstrated and commercialized for industrial steam boiler waste heat and water recovery. A 40% recovery of the exhaust water vapor and an increase of more than 5% in efficiency have been achieved [19].

Swamee et al. formulated the optimal design of the exchanger as a geometric programming with a single degree of difficulty. The solution of the problem yields the optimum values of inner pipe diameter, outer pipe diameter and utility flow rate to be used for a double pipe heat exchanger of a given length, when a specified flow rate of process stream is to be treated for a given inlet to outlet temperature [20].

Bergeles et al. presented the understanding of the mechanism of ash deposition on the surfaces of tubes of heat exchangers in lignite utility boilers and the evaluation of the influence of fouling on heat exchanger efficiency. Heat transfer is concerned, the closer spaced staggered arrangement seems to behave more efficiently and for the same spacing the staggered arrangement is still more efficient than the in-line one. However, closely spaced tubes increase fouling of the heat exchanger while the first tube rows are the ones most prone to fouling and hence capture more particles than subsequent rows. Generally the tubes in the tube bundle arrangement intercept particles flowing through the tube bundle and interception is the most prominent deposition mechanism; the tube arrangement influences the fouling rate by affecting the flow field so future research might be directed towards different tube shapes and arrangements that will facilitate particle by-pass of the tubes. Possible solutions could be the use of streamline tube shapes or the use of tubes that do not play any role in heat transfer as particle traps for the first rows of the tube bundle [21].

Maziasz et al. focused on the behaviour and performance improvements of sheets and foils of various alloys for compact heat-exchangers (recuperator) for advanced micro-turbines. The performance and reliability of such thin sections are challenged at 650–750 ◦C by fine grain size causing excessive creep, and by moisture effects greatly enhancing oxidation attack in exhaust gas environments. Standard type 347 stainless steel has been used successfully at or below 600 ˚C, but has suffered from both of these kinds of degradation at 650 ˚C and above. Alloys have been identified which can have very good properties for such heat-exchangers, especially with careful control of microstructure during processing, including alloy 625, HR120 and the new AL20-25+Nb. These alloys, and the mechanistic understanding behind their behaviour, are also applicable to achieving the better heat-exchanger technology needed for fuel cells or other high-temperature, clean-energy applications [22].

Kumar and Khanam attempted to conserve energy in coal based sponge iron industry incorporating certain design modifications without disturbing the process technology. To recover heat from these areas two design modifications, Case-1 and Case-2, are proposed. Preheating of air up to 170 ◦C for Case-1 reduces coal consumption by 8.7%. Consequently, waste gas generation reduces by 16.7%. Thus, for Case-1 profit is Rs 9.6 million/year. However, for Case-2 preheating of air to 80 ◦C before entering the kiln reduces coal and water consumption by 7.2% and 96.3%. Consequently, cooling tower capacity is reduced by 37.2%. Due to 27.8% less profit for Case-1 in comparison to Case-2 Case-1 offers higher payback period than that of Case-2. Thus, Case-2 is selected as best proposed design [23].

Alkhamis et al. discussed about design, manufacture, installation and analyse to utilize the sensible heat contained in the exhaust gas stream out of the kitchen furnace. The results of the research indicate that more than 60% of the waste heat from the kitchen furnace can be recovered and that the investment in such coil heat exchanger system is highly economical [24].

Zhao et al. investigated the effects of corrosion on the fin-and-tube heat exchangers with different fin materials during long-term use was performed. The overall heat transfer coefficient of the sample with Cu fins was on average 55.8%, 67.4%, and 69.4% more than that of the sample with Al fins before and after the 48 and 96 h salt spray tests, respectively. From the thermal resistance standpoint, the corrosion factor in the overall thermal resistance of the heat exchanger was 19.4% and 14.8% for the sample with Al fins and with Cu fins after the 48 h salt spray test, respectively. After the 96 h salt spray test, the proportions for these two samples was 27% and 19.1%, respectively [25].

Pint and Peraldi attempted to provide a clear, fundamental understanding of alloy composition effects on corrosion resistance of stainless steel components used in recuperator, the oxidation behaviour of model alloys is being studied. A composition range of Cr and Ni contents has been identified with better corrosion resistance than type 347 stainless steel. Finer-grained alloys showed improved corrosion resistance compared to coarse-grained alloys with the same composition. It also has been demonstrated that minor alloy additions of Mn and Si are beneficial to corrosion resistance in these environments [26].

Wilson et al. discussed about silicon carbide (SiC) based micro-channel recuperator concepts are being developed and tested. A typical micro-turbine cycle was modified and modeled to incorporate this ceramic recuperator and it was found that the overall thermal efficiency of the micro-turbine could be improved from about 27% to over 40%.could be improved from about 27% to over 40% [27].

PART 3

INDUSTRIAL PROCESS HEATING FURNACES

Industrial process heating furnaces are insulated enclosures designed to deliver heat to loads for many forms of heat processing. Melting ferrous metals or glasses require very high temperatures, and may involve erosive and corrosive conditions. Shaping operations use high temperatures to soften many materials for processes such as forging, rolling, pressing, bending, and extruding. Treating may use midrange temperatures to physically change crystalline structures or chemically (metallurgical) alter surface compounds, including hardening or relieving strains in metals, or modifying their ductility. These include aging, annealing, carburizing, hardening, stress-relieving, and tempering. Industrial processes that use low temperatures include drying, polymerizing, and other chemical changes [28].

In the metal industry, many furnaces are used to promote physical changes such as heating to soften the metal for further shaping, re-melting for casting, and annealing to promote changes within the crystalline structure or to relieve stresses introduced during the manufacturing process [29].

3.1. FURNACE CLASSIFICATION

Batch-type furnaces and kilns, defined “in-and-out furnaces” or “periodic kilns” have one temperature set point, but via three zones of control to maintain uniform temperature distribution, because of a need for more heat at a door or the ends. They may be loaded manually or by a manipulator. Loads are placed in the furnace and dependently the process, furnace and loads are brought up to temperature together, the furnace may or may not be cooled before it is opened and the load removed generally through a single charging and discharging door [28]. Different configurations of batch type furnaces are given in Figure 3.1.

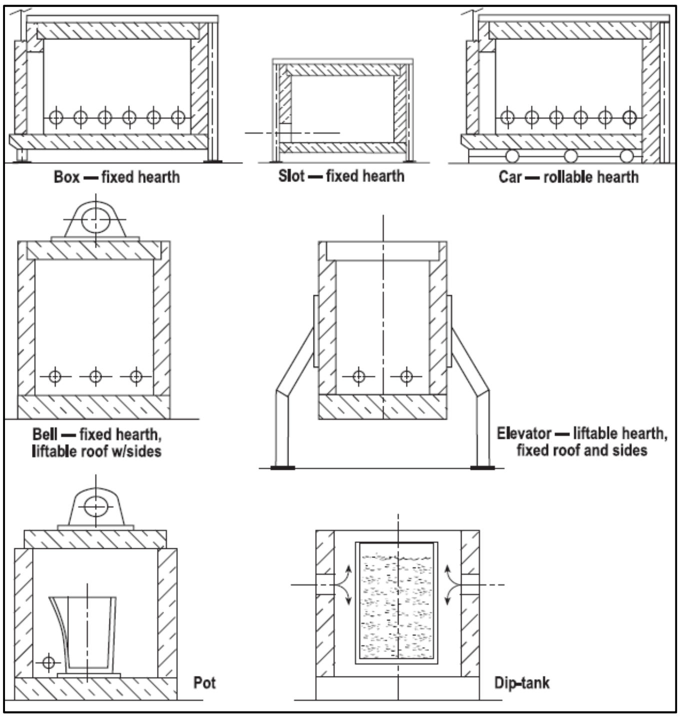


Figure 3.1. Seven (of many kinds of) batch-type furnaces [28].

A good example of a batch type furnace is an ingot reheating furnace as shown in Figure 3.2 which shows a large steel ingot about to be discharged to be forged into a blank for a large steam turbine shaft. The efficiency of this operation is low for a number of reasons, including the fact that it is impractical to recover heat from the product following forging and the heat embedded in the furnace structure is lost on cooling owing to the cyclic nature of the operation [29].

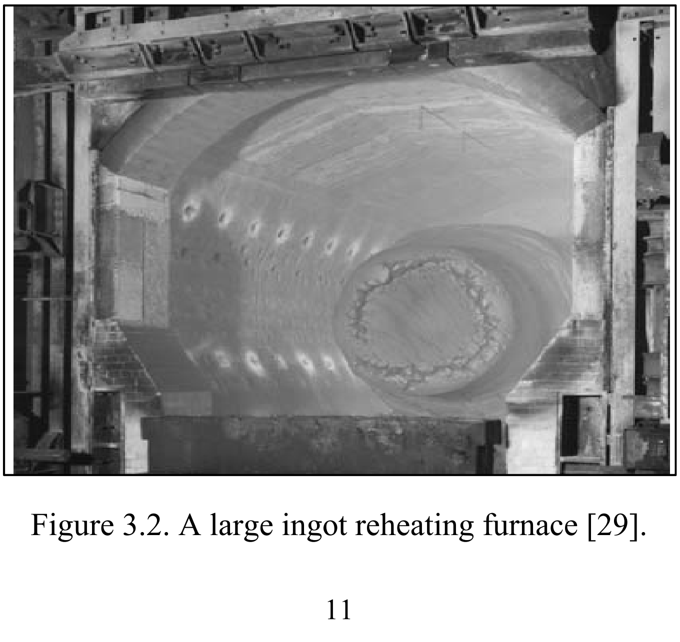


Figure 3.2. A large ingot reheating furnace [29].

Another configuration of a furnace used for physical processing of metal is the annealing furnace, used to stress relieve large fabrications. During stress relieving or annealing, the completed fabrication is heated at a controlled rate and held for an extended period at one or more ‘ soaking temperatures ’ for the stresses to equalise or certain crystal changes to occur. These processes are normally batch processes.

Figure 3.3 shows two large gearbox cases are entering in an annealing furnace. This furnace has a conventional refractory lining and, as a consequence, the energy lost during cooling will be significant. These losses could be considerably reduced if the furnace had a ceramic fibre lining, since the energy used in heating this type of lining is much less than for brick and hence less energy is also lost during cooling [29].

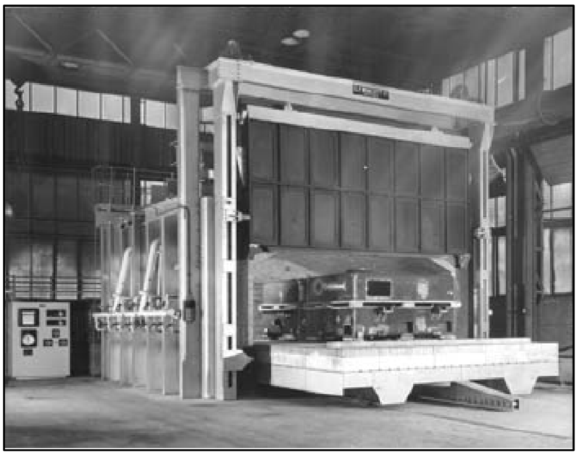


Figure 3.3. Two large gearbox cases entering a large annealing furnace [29].

Car-hearth (car type, car bottom, lorry hearth) furnaces, sketched in Figure 3.1, have a movable hearth with steel wheels on rails. The load is placed on the car-hearth, moved into the furnace on the car-hearth, heated on the car-hearth, and removed from the furnace on the car-hearth; then the car is unloaded. Cooling is occurred on the car hearth either in the furnace or outside before unloading. This type of furnace is used mainly for heating heavy or bulky loads or short runs of assorted sizes and shapes [28].

Continuous furnaces move the charged material, stock, or load while it is being heated. Material passes over a stationary hearth or the hearth itself moves. If the hearth is stationary, the material is pushed or pulled over skids or rolls, or is moved through the furnace by woven wire belts or mechanical pushers. Except for delays, a continuous furnace operates at a constant heat input rate, burners being rarely shut off. A constantly moving (or frequently moving) conveyor or hearth eliminates the need to cool and reheat the furnace (as is the case with a batch furnace), thus saving energy [28].

Continuous furnaces are importantly suitable for energy recovery and minimise the heat lost on furnace shutdown. Figure 3.4 shows continues type billet reheating furnace. This furnace type achieves high energy efficiency by using high velocity burners and this provides really high rate of heat transfer to the load. Combustion is completed at the burner exit nozzle and uniform gas flows ensure high rates of convective heat transfer without forming ‘ hot spots ’ on the surface that would result in steel degradation. The heated billets discharged on conveyors to transport into the forging machine. The flue gases pass over the load and preheat the incoming billets by counter-current heat transfer with the outgoing combustion products [29]. The disadvantage of them is the limited flexibility to maintain this high rate efficiency. The gas velocity across the billets must be high to achieve the required heat transfer. Effective heat recovery is only achieved for only a limited range of billet sizes.

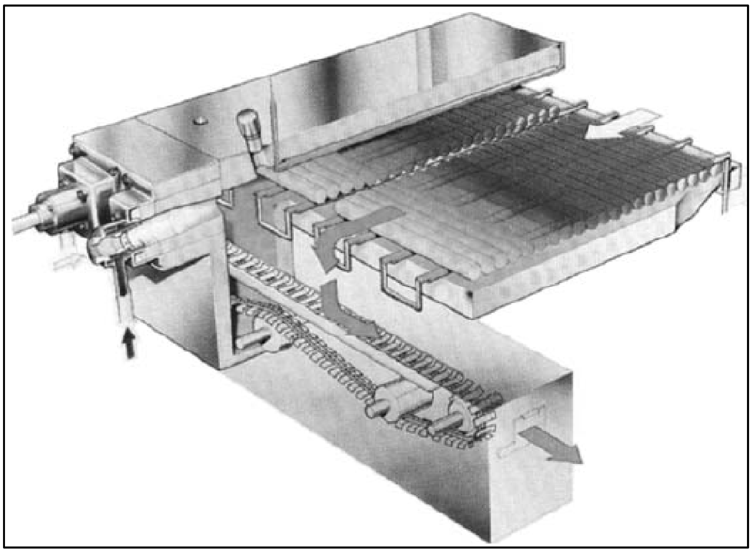


Figure 3.4. Continuous rapid heating furnace for small billets [29].

3.2. REHEATING FURNACE

An important class of continues type heating furnace for metal industry is the reheating furnace. The main objective of a reheating furnace is to provide properly reheated slabs, blooms, or tubes to a rolling mill. The desired characteristics of a reheating furnace include:

a) Correct stock discharge temperature.
b) Proper temperature distribution along the length of the stock.
c) Low temperature difference between the surface and the core of the stock.
d) Thermally efficient.
e) Minimum scale formation on the stock surface.
f) Low maintenance and high availability.
g) Minimized operation and capital costs.

A standard steel reheat furnace consists of the following components: heating chamber or furnace, hearth or support for carrying the charge, controls to maintain a specified temperature, distribution system for heating and waste gas removal, and a materials handling system for moving the charge into and out of the furnace. The required material outlet temperature depends on its composition and geometry and can be as high as 2350°F (1290°C) [30].

A common slab reheating furnace is shown in Figure 3.5. It consists of three zones such as a preheating zone, a heating zone and a soak zone. The slabs lie horizontally and are heated by burners from upper and lower regions. The slabs are transported through the furnace by refrigerant cooled ‘walking beams’ , or by a ‘pusher’ installed at the cold end that pushes the slabs on cooled skids. The slab enters the preheating zone, where it is heated to approximately 500° C. The heating rate must be sufficiently slow to prevent the overheating of slab outer surface and forming a reflective slag. If a reflective slag is formed, the radiant heat transfer is reduced in subsequent zones.

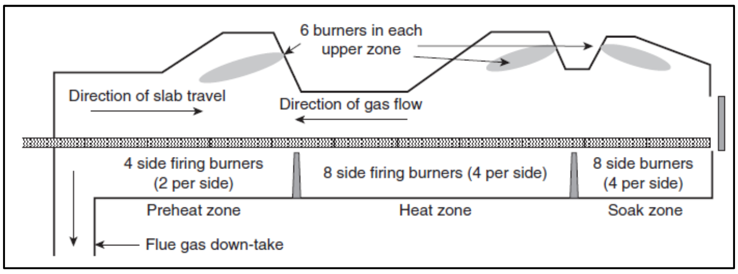


Figure 3.5. Schematic illustration of slab reheating furnace [29].

In some furnaces load recuperation from the flue gases similar to that in slab reheating furnace above is employed prior to the preheat zone. This improves inherent furnace efficiency and reduces the flue gas temperature prior to the recuperator, thus reducing recuperator inlet metal temperature and potentially prolonging its life. Preheating is followed by the main heat zone, where the majority of the heat transfer takes place, and the soak zone where temperature equalisation through the slab occurs. The slab reheating furnace shown above is effectively a continuous process with slabs being fed and discharged approximately every ten minutes or so [29].

Heat balance diagram of a slab reheating furnace is illustrated in Figure 3.6. Hot flue gas takes away 31.36% of the energy from the furnace system. In other words, near one-third heat of the system is contained in the gas, which is leaving from the furnaces. Therefore, if one is able to recover the energy from the hot flue gas sufficiently, a large amount of fuel can be saved [6].

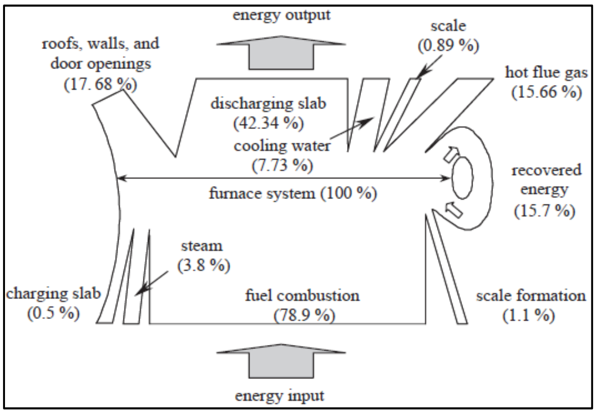


Figure 3.6. Heat balance diagram of energy input and energy output of the reheating furnace system [6].

3.2.1. Efficiency Effecting Factors of a Reheating Furnace

a) Air Fuel Ratio.
b) Incomplete combustion.
c) Flue gas temperature.
d) Recuperator.
e) Surface heat losses.
f) Scale loses.
g) Cooler loses.
h) Leakages.
i) Fuel type.
j) Burners.
k) Product discharge temperature.

Incomplete combustion refers to unburned combustible substances is released in flue gas from the chimney. Incomplete combustion cause the fuel loses and air pollution. Air fuel ratio is another factor for optimum complete combustion and really important parameter for reheating furnace efficiency and product quality. High temperature flue gas is a high energy transporter from system to environment and major amount of energy losses in this way. Problems and leakages in recuperator affect the combustion air and so directly affect the combustion. Heat loses from non-isolated surfaces has the big proportion to take care. During this reheating operation, hot steel surfaces react with the in-furnace oxidizing atmosphere resulting in the formation of an iron oxides layer (scale). The yield loss due to this phenomenon depends on furnace operating conditions, i.e. steel temperature, excess combustion air, steel residence time in the furnace, etc., and ranges between 1.5 to 3% of reheated steel [31]. Scale formation affects the heat transfer negatively and so energy loses occurs and affects the product quality. Doors of furnace and openness cause the heat loses. Setting of the burners about the type of fuel affects the combustion efficiency.

3.3. FORGING

Forging is a metal forming process used to change the shape of metal parts by using compressive forces, often with the use of a die, to give the desired shape. This can be done in a batch or continuous process, depending upon the part geometry, material temperature and material composition. Forging may be applied when the part is hot or cold. Hot parts may require energy to heat them up, but require lower compressive forces for shaping. Cold forging does not require any energy to heat the part, but does require higher compressive forces for shaping. Hot forging is of interest here because it usually requires fossil fuel combustion to do the heating, because electric induction heating is often expensive [30].

3.4. ENERGY EFFICIENCY IMPROVEMENT CONSIDERATIONS FOR INDUSTRIAL FURNACES

Potential energy efficiency improvements of a furnace can be achieved by optimum design and operation conditions. The most common efficiency improvement considerations are:

a) Minimum air leakage.
b) Low excess air combustion in the burners to maximise heat transfer.
c) Waste heat recovery from the products and flue gases.

PART 4

WASTE HEAT

Waste heat refers to the energy that is generated during a process and released without being put to practical usage. Sources of waste heat are hot combustion flue gas releasing to the atmosphere and heat transfer from hot surfaces. The exact quantity of industrial waste heat is poorly quantified, but various studies have estimated that as much as 20 to 50% of industrial energy consumption is ultimately discharged as waste heat [32].

Sources of waste energy can be divided into three temperature interval according to temperature.

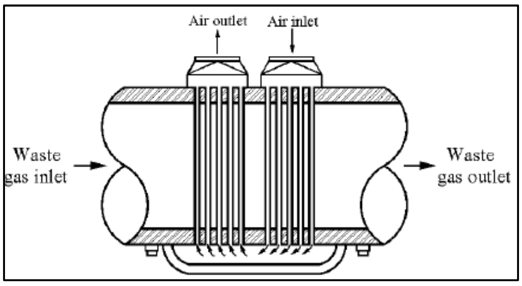
a) The high temperature range is above 650 ^oC.
b) The medium temperature range is between 230 ° C and 650 ^oC.
c) The low temperature range is below 230 °C.

4.1. WASTE HEAT RECOVERY

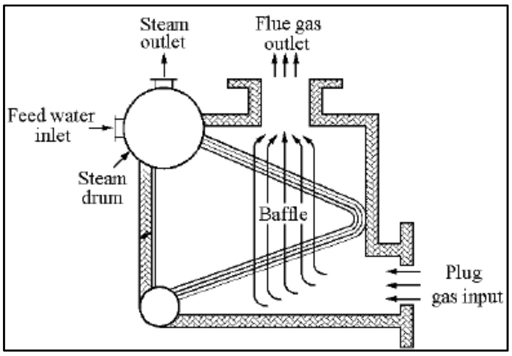
Waste heat recovery implies capturing and reusing the waste heat for heating or for generating mechanical or electrical work in an industrial process. Some common industrial waste heat applications are preheating combustion air or furnace loads, generating electricity, and space heating. Heating combustion air can raise boiler efficiency about 1% for every 22 °C in temperature increase [33]. An amount of waste heat losses from industrial processes are inevitable. Facilities can reduce these losses by using heat recovery equipment and improving the system efficiency. Heat recovery systems commonly reduce the operation costs for facilities by increasing the energy productivity.

4.1.1. Energy Conservation by Waste Heat Recovery from Flue Gases

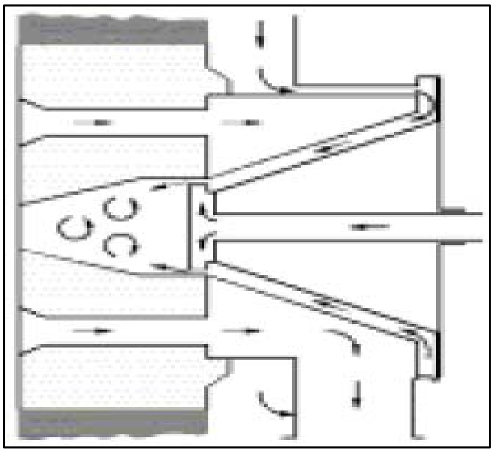
The heat loss from flue gas of a furnace is around 10 – 40 % and can be recovered by methods are illustrated in Figures 4.1.(a, b, c, d, e, f, g, h) [34].



a) Preheating combustion air by recuperator,

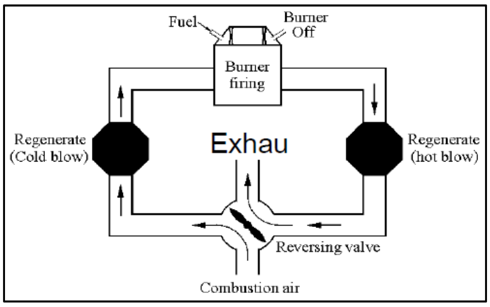


b) Generating steam by a waste heat boiler,

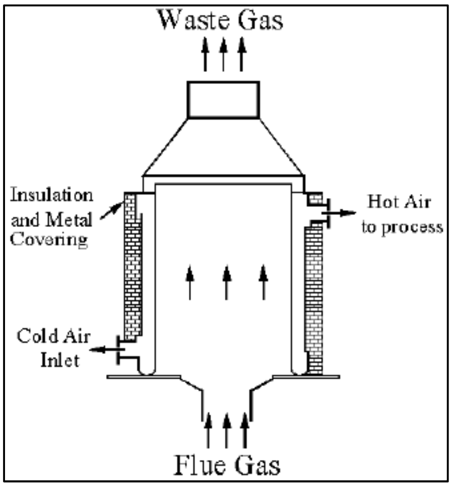


c) Preheating combustion air by recuperative burner,

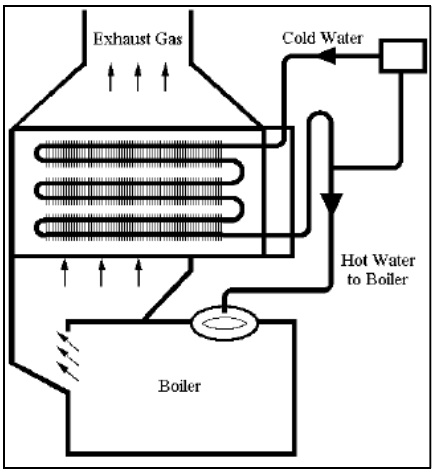
Figures 4.1. Hot flue gas recovering methods [34].



d) Preheating combustion air by regenerator,

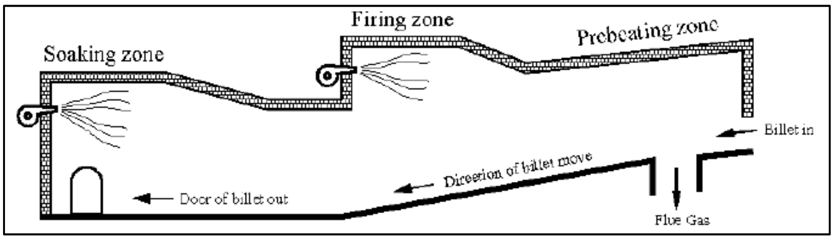


e) Preheating combustion air by an air preheater,

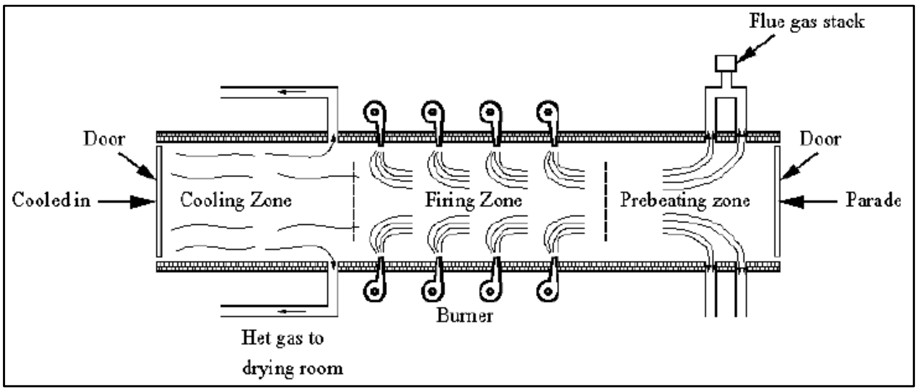


f) Preheating boiler feed water by an economizer,

Figures 4.1. (Continue)



g) Preheating materials by add preheating zone,



h) Using in processes such as drying process or hot liquid generating process.

Figure 4.1. (Continue).

Sankey diagram (visual heat balances) illustrates the heat flow in a furnace. Heat flow for a furnace without air preheater and with an air preheater is illustrated in Figure 4.2 and Figure 4.3.

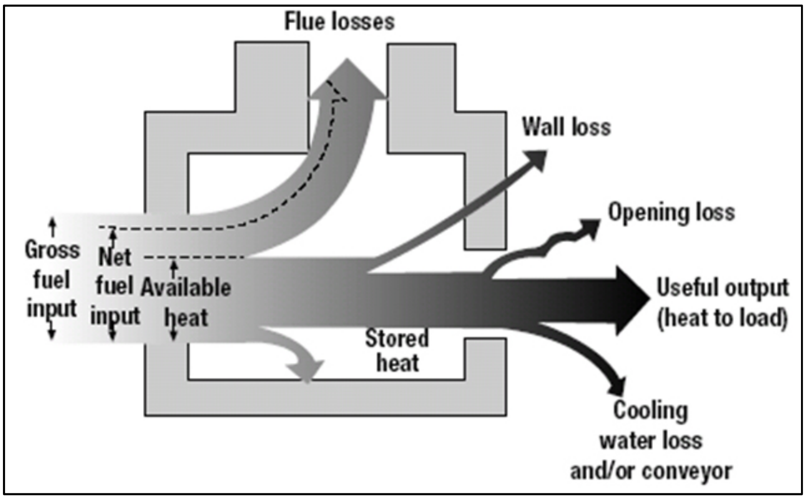


Figure 4.2. Sankey diagram for a furnace without an air preheater [35].

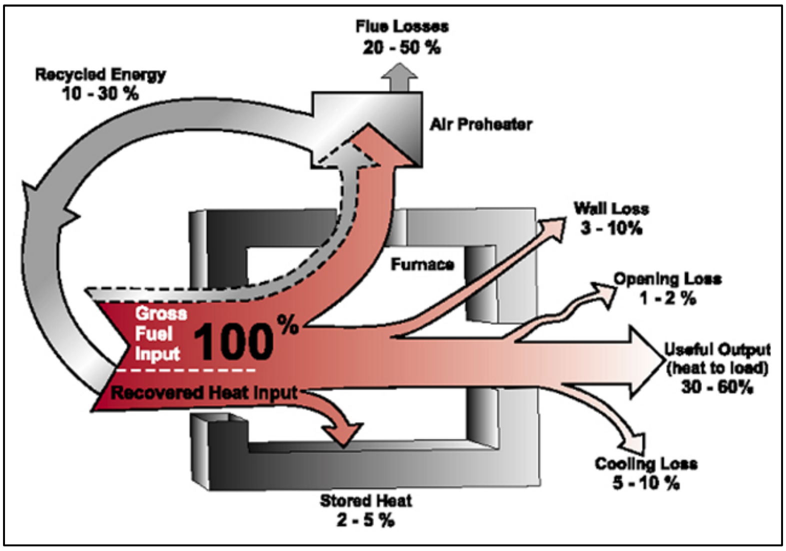


Figure 4.3. Sankey diagram of a furnace with an air preheater [35].

4.2. WASTE HEAT RECOVERY BY A HEAT EXCHANGER

Heat recovery is undertaken in equipment that is used to transfer the waste heat from one high temperature medium to low temperature one is generally classified by the term heat exchanger. Heat exchangers are frequently used to improve the efficiency of a system.

While they all perform the same function, there are considerable variations in the design of them according to the physical and chemical properties of the hot and cold fluids.

Some general observations can be applied about the design methodology of heat exchangers. They can be divided into two major groups, recuperative and regenerative, which are shown in Figure 4.4. Recuperative exchangers transfer heat continuously between two fluids, either by direct contact or through a thermally thin dividing surface. Regenerative heat exchangers use a thermally absorbent sink to store heat from the hot fluid medium and then discharge heat to the cold fluid medium in a cyclic mode. Thus, recuperative heat exchangers operate in a steady state mode, whilst regenerative heat exchangers operate in an unsteady state mode.

Some configurations of heat exchangers are built into the burners, but more commonly they are attached to the system separately.

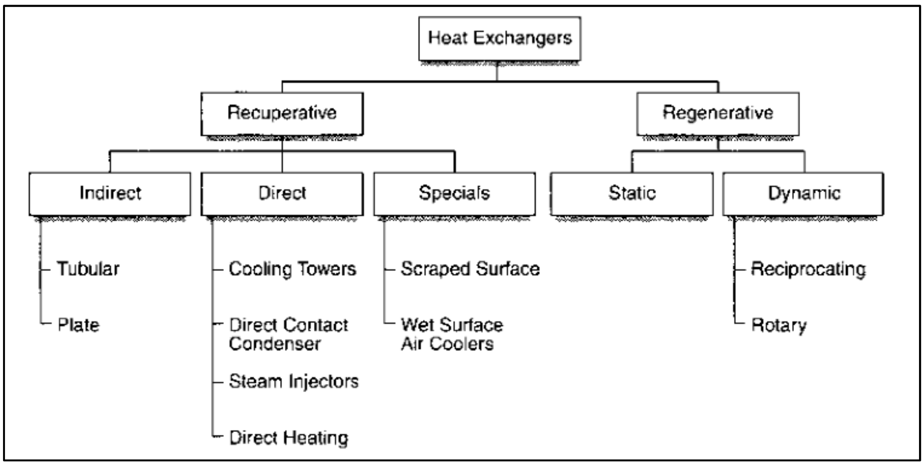


Figure 4.4. Heat exchanger classifications [30].

4.3. GENERAL HEAT EXCHANGER DESIGN PROCEDURE

The design procedure of a heat exchanger directly depends on the working conditions. Heat exchangers are knows as pressure vessel in literature and dominant design parameters are pressure, temperature and materials. Generally 150 mm diameter pipe and pressure difference between the surfaces is about 1 atm closed systems are classified as pressure vessel [36]. Usually, the inlet and outlet temperatures and flow rates of the two streams are fixed by the process requirements, design is proceeded by the correct sizing of the heat exchanger to provide required heat transfer surface area. It is also generally, there are pressure drop limitations for the fluids, governed by economic pumping or fan power considerations. The pressure drop depends on the fluid velocity, the flow channel equivalent diameter, and the channel length. There is only one optimum design, despite an infinite number of solutions.

Assumption of a particular design matrix (i.e. fix the tube channel size and spacing) and velocities of the two fluids are the simplest approach. The required heat transfer area and pressure drops for the two fluids are then calculated by using the basic design equations.

The optimum design is then carried out and the first estimation is improved, in the light of existing design knowledge. After a series of iterations, the optimum design is fixed. This is a relatively easy, but tedious design procedure.

More precious design theory can be developed, by using the basic heat transfer and pressure drop equations as functions of tube length, diameter, fluid properties and flow rate. A generalised calculation procedure can be applied on yielding simultaneous equations for heat transfer and pressure drop. Then calculation is occurred analytically, graphically or by computation. This design method requires a remarkable development investment of operator to ensure the stability and reliability of the method over the design range.

4.3.1. Recuperative Heat Exchanger Design Theory

Transfer of heat from hot flue or process gases is often encountered in industrial processes e.g. fire-tube boiler operation, waste heat recovery from flue gas etc. A simplified equation for the calculation of tube side heat transfer coefficient for common gases has been given as [37]:

$$h_i = 12.58 c_p \frac{G^{0.8}}{D^{0.2}} \tag{4.1}$$

For recuperative units, the general design equation for the heat transferred, Q, can be written as:

$$Q = UA\Delta T_{lm} \tag{4.2}$$

Where: The overall h.t.c,

$$U = \frac{1}{\frac{1}{h_{inside}} + \frac{x}{k} + \frac{1}{h_{outside}}} \tag{4.3}$$

And the logarithmic mean temperature difference,

$$\Delta T_{lm} = \frac{\Delta T_{out} - \Delta T_{in}}{\ln\left(\frac{\Delta T_{out}}{\Delta T_{in}}\right)} \tag{4.4}$$

There are four basic configurations for the arrangement of the flows into and out of recuperative exchangers. These are shown in Figure 4.5. In co-current or parallel-flow units the two fluid streams enter together at one end, flow through in the same direction, and leave together at the other end ($\Delta T_{in} = T2_{in} - T1_{in}, \Delta T_{out} = T2_{out} - T1_{out}$); whereas in counter-current or counter-flow units the two fluid streams move in opposite directions ($\Delta T_{in} = T2_{out} - T1_{in}, \Delta T_{out} = T2_{in} - T1_{out}$).

In single-pass cross-flow units, one fluid moves through the heat transfer matrix at right angles to the flow path of the other fluid. In multi-pass cross-flow units one fluid stream shuttles back and forth across the flow path of the other fluid stream, usually giving a cross-flow approximation to counter-flow. The most important differences between these four basic types lies in the relative amounts of heat transfer surface area required to produce a given temperature rise for a given temperature difference between the two fluid streams where the primary fluid enters the heat exchanger [29].

Heat transfer rate and surface are relationship for different flow regime recuperators are given in Figure 4.6.

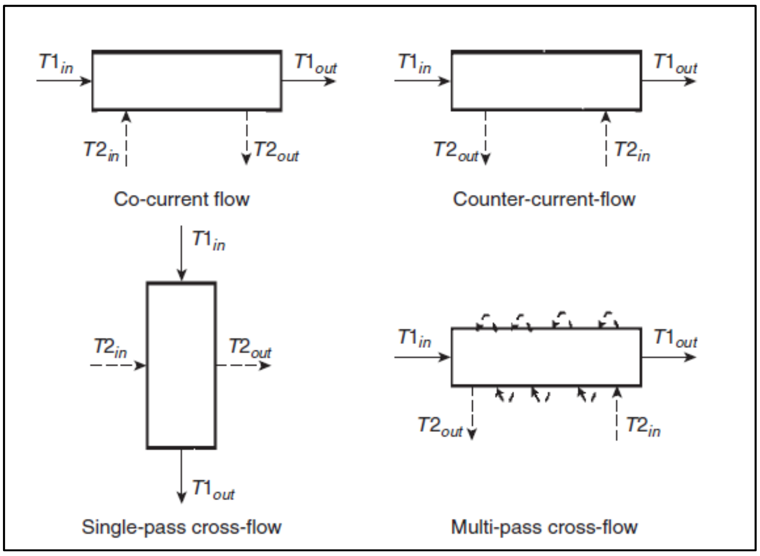


Figure 4.5. Types of flow path configurations through the recuperative heat exchangers [29].

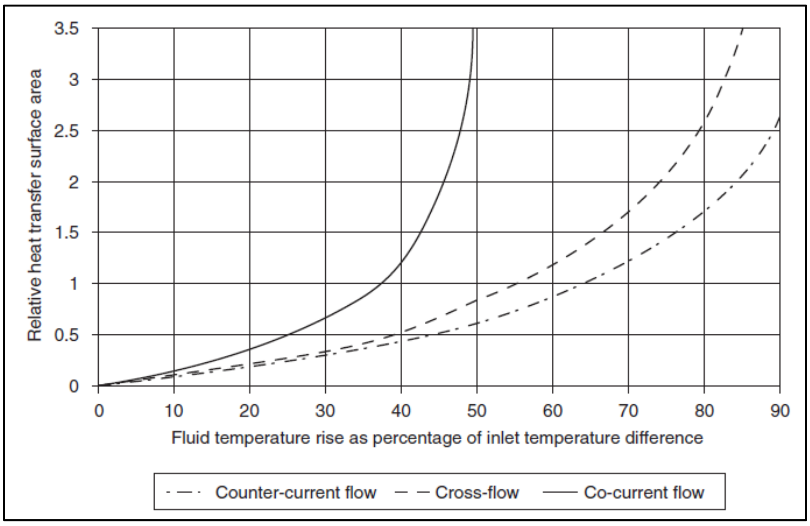


Figure 4.6. Relationship between heat transfer rate and surface area for different recuperative heat exchanger flow regimes [29].

In order to get a very high value of efficiency only the counter-current flow configuration and the multi-pass one should be considered. The single-pass cross-flow configuration is not a valid choice since the heat exchanger would work in such a way that a very large part of it does not contribute actually to the overall thermal exchange, because of the small difference between the stream temperatures [38].

PART 5

GAS TO GAS HEAT EXCHANGERS

According to the heat transfer standpoint, the best gas to gas heat exchanger design is usually one in which the flue gas is pulled though relatively large passages while the air is pushed through smaller passages at high velocity. This also assures that any leaks (and there will eventually be some leaks) will not dilute the combustion air and upset control of the combustion process.

If leaks should happen to occur from air side to gas side, they will reduce the quantity of preheated air (lowering overall combustion efficiency) and cool the flue gases, lowering the ΔT that is the driving force for heat flow from flue gases to combustion air [28].

5.1. RECUPERATOR

Recuperator is a heat exchanger which uses sensible energy from hot flue gas to preheat the combustion air. The flue gas and air are flowing in adjacent passageways separated by a conducting wall. Heat flows steadily through the wall from the high temperature medium (hot flue gas) to the low temperature medium (cold combustion air).

The term “heat exchanger effectiveness” called ‘pickup’ as applied to recuperator, means the actual air temperature rise expressed as a percentage of the maximum possible air temperature rise. Commercial recuperators are usually designed for a 60% to 75% range. Higher pickup ratios result in larger and more expensive recuperator. Regenerators have higher heat exchanger effectiveness than recuperators, and they avoid some of the difficulties inherent in recuperators [28].

Recuperators are available in many configurations. Common forms are double pipe (pipe in a pipe), shell and tube, and plate types. They can be classified according to the flow configurations as counter-flow, parallel (co-current) flow, and/or cross flow. Counter flow type recuperators deliver higher air preheats temperature, but parallel flow type recuperators protect the walls from overheating and consequently extending its service life. Therefore, the hot flue gas is often fed first to a parallel flow section and then to a counter flow section to benefit from both advantages.

If the heat transfer coefficients, h, were constant, the curve in Figure 5.1 would be logarithmic. However, there is considerable variation in the value of the coefficient, depending on the temperature of gas and air, density and velocity of gas and air, afterburning, radiation, leakage, and the character of the heat exchanging surface [28].

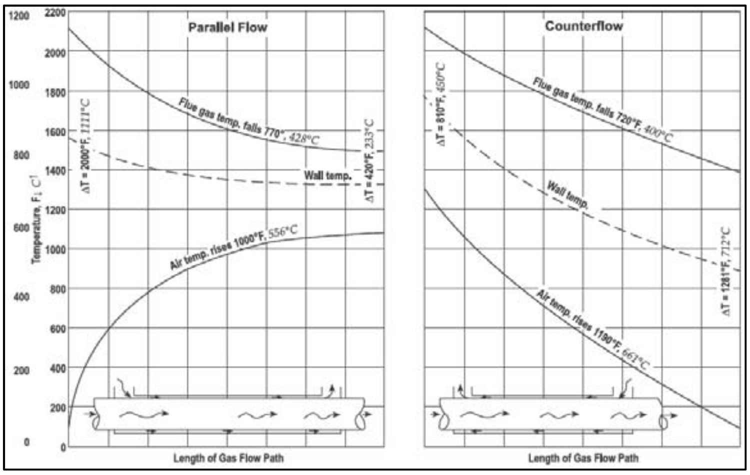


Figure 5.1. Comparison of temperature patterns in parallel flow and counter-flow recuperators [28].

The simplest form of recuperator is the metallic radiation recuperator which consists of two concentric lengths of metal tubing as shown in Figure 5.2**.** Two different fluids flow into separated inner tube and external annulus without mixing. The flowing hot flue gas in the inner tube is cooled down and heats combustion air, flows into the external annulus. Combustion air gains energy and increase the combustion efficiency.

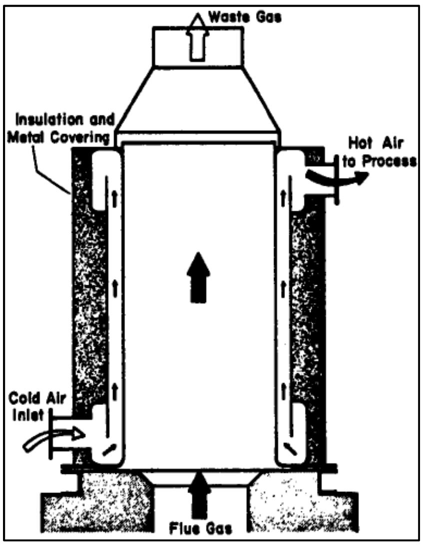


Figure 5.2. Diagram of metallic radiation recuperator [39].

Additionally, fuel saving promote decrease in combustion air, thus stack losses are decreased not only by lowering the stack gas temperatures but also by discharging little quantities of exhaust gas. This recuperator takes its name from the fact that a major portion of the heat transfer from the hot gases to the surface of the inner tube occurs by radiation.

A second common configuration is called the tube type or convective recuperator. As shown in Figure 5.3, the hot flue gas is carried through a number of parallel small diameter tubes, while the incoming air to be heated enters a shell surrounding the tubes and passes over the hot tubes one or more times in a direction normal to their axes.

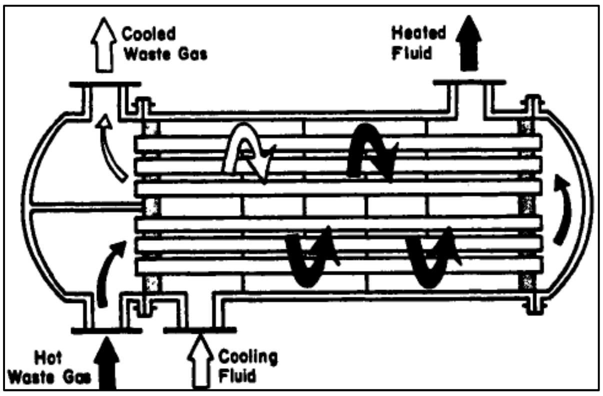


Figure 5.3. Diagram of convective-type recuperator [39].

If the tubes are baffled to allow the gas to pass over them twice, the heat exchanger is termed a two-pass recuperator; if two baffles are used, a three-pass recuperator, etc. Although baffling increases both the cost of the exchanger and the pressure drop in the combustion air path, it increases the effectiveness of heat exchange. Shell and tube type recuperators are generally more compact and have a higher effectiveness than radiation recuperators, because of the larger heat transfer area made possible through the use of multiple tubes and multiple passes of the gases [39].

Recuperators are produced by different materials according to the working condition limitations of materials. Lower temperature recuperators are normally made of metal, while higher temperature recuperators may be made of ceramics [30].

The inner tube is often fabricated from high temperature materials such as stainless steels of high nickel content. The high temperature differential at the inlet causes differential expansion, since the outer shell is usually of a different and less expensive material. This condition mechanically must be taken into account in the design procedure. More elaborate design of a radiation recuperator incorporates two sections: the bottom operates in parallel flow and the upper section using the more efficient counter-flow arrangement. Because of the large axial expansions experienced and the stress conditions at the bottom of the recuperator, the unit is often supported at the top by a free-standing support frame with an expansion joint between the furnace and recuperator.

The principal limitation on the heat recovery of metal recuperator is the reduced life of the liner at inlet temperatures exceeding 1000°C. At this temperature, it is necessary to use the less efficient arrangement of parallel flows of exhaust gas and coolant in order to maintain sufficient cooling of the inner shell. In addition, when furnace combustion air flow is dropped back because of reduced load, the heat transfer rate from hot waste gases to preheat combustion air becomes excessive, causing rapid surface deterioration. Then, it is usually necessary to provide an ambient air bypass to cool the exhaust gases.

In order to overcome the temperature limitations of metal recuperators, ceramic tube recuperators have been developed whose materials allow operation on the gas side to 1500°C and on the preheated air side to 1200°C on an experimental basis and to 815°C on a more or less practical basis. Early ceramic recuperators were built of tile and joined with furnace cement, and thermal cycling caused cracking of joints and rapid deterioration of the tubes. Later developments introduced various kinds of short silicon carbide tubes which can be joined by flexible seals located in the air headers. This kind of patented design illustrated in Figure 5.4 maintains the seals at comparatively low temperatures and has reduced the seal leakage rates to a few percentages. Earlier designs had experienced leakage rates from 8 to 60 percentages. The new designs are reported to last two years with air preheat temperatures as high as 700 ^{o}C, with much lower leakage rates [39].

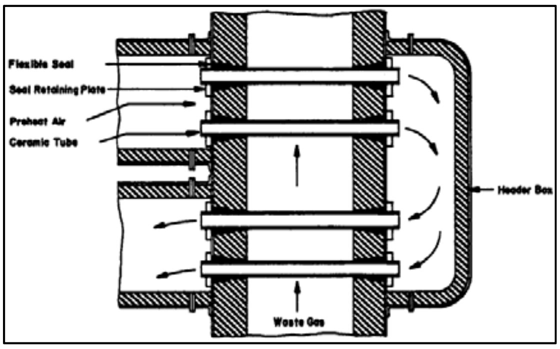


Figure 5.4. Ceramic recuperator [39].

An alternative arrangement for the convective type recuperator, in which the cold combustion air is heated in a bank of parallel vertical tubes that extend into the flue gas stream, is shown schematically in Figure 5.5. The advantage claimed for this arrangement is the ease of replacing individual tubes, which can be done during full capacity furnace operation. This minimizes the cost, the inconvenience and possible furnace damage due to a shutdown forced by recuperator failure [39].

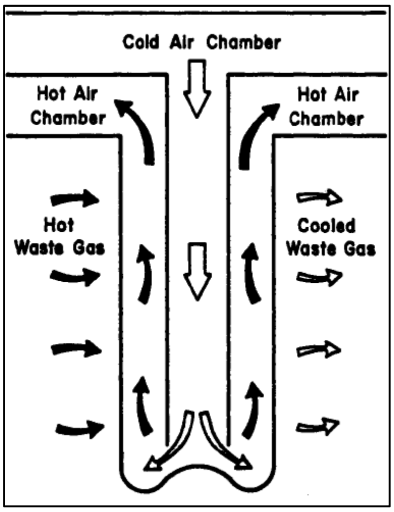


Figure 5.5. Diagram of vertical tube-within-tube recuperator [39].

For maximum effectiveness of heat transfer, combinations of radiation type and convective type recuperator is used, with the convective type always following the high temperature radiation recuperator. A schematic diagram of this arrangement is shown in Figure 5.6.

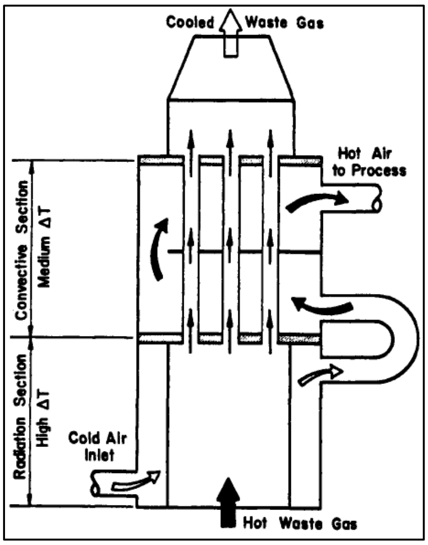


Figure 5.6. Diagram of combined radiation and convective type recuperator [39].

The use of a recuperator, which raises the temperature of the incoming combustion air, may require purchase of high temperature burners, larger diameter air lines with flexible fittings to allow for expansion, cold air lines for cooling the burners, modified combustion controls to maintain the required air/ fuel ratio despite variable recuperator heating, stack dampers, cold air bleeds, controls to protect the recuperator during blower failure or power failures and larger fans to overcome the additional pressure drop in the recuperator. It is vitally important to protect the recuperator against damage due to excessive temperatures, since the cost of rebuilding a damaged recuperator may be as high as 90% of the initial cost of manufacture, and the drop in efficiency of a damaged recuperator may easily increase fuel costs by 10% to 15% [39].

Recuperator concerns stem mostly from fouling of the heat transfer surfaces, overheating damage, and leaks. Flame, direct furnace radiation, or condensation should never be allowed to enter any heat recovery equipment [28]. One factor that should be concerned in recovering waste heat from flue gas is the dew point temperature of sulphuric acid (H_2SO_4) if the fuel composes of sulphur. So the temperature of flue gas at the exit of the heat exchanger that used for calculating available recovering heat must beyond 180 °C and the recuperator efficiency is 70% [34]. Recuperator design requires the take in to account these undesirable effects. Recuperator failures could be controlled by the following means.

a) Use of corrosion-resistant and clad metal (bimetal) materials.
b) Use of fluids with corrosion inhibitors.
c) Good design, avoiding crevices, stagnant fluid zones, upgrading materials, having uniform and optimum fluid velocities (not too high or too low in the exchanger), using solid non-absorbent gaskets (e.g., Teflon), minimizing tensile and residual stresses in exchanger surfaces, designing for desired start-ups and shutdowns, and so on.
d) Proper selection of construction metals from the point of proximity in the galvanic series.
e) Surface coatings, surface treatment, electrochemical protection, and so on Maintaining clean exchanger surfaces (no deposits) and fluids (use a filter in the flow circuit).
f) Avoiding aluminium alloys if erosion corrosion cannot be prevented [40].

Table 5.1. Standard of flue gas heat recovery [28].

Flue gas temperature (^0C)	Percentage of exhaust gas heat recovery (%)		
	84 GJ/h	21-84 GJ/h	4.2-21 GJ/h
< 600	25	25	-
600-800	35	30	25
800-900	40	30	25
> 900	45	35	30

Table 5.1 gives the standard heat revovery ranges from different temperature levels flue gases.

The air flow rate through a recuperator must never drop below 10% of its design flow rate until the furnace cools down several hours.

Ducting between a recuperator and a furnace must be in Figure 5.7. Top views of system in Figure 5.7 are shown about damage to the recuperator; the lower two views are shown about damage to the furnace load.

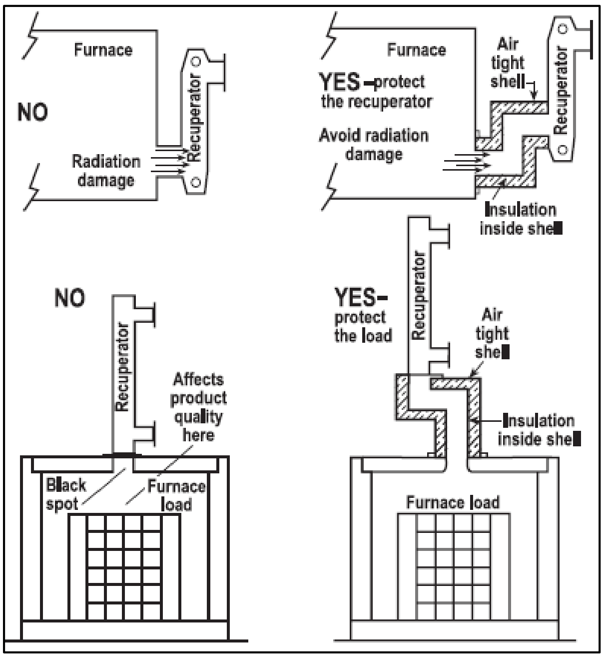


Figure 5.7. Recuperator installation [28].

Correct recuperator installation prolongs the recuperator life and provides uniform temperature distribution in the heated loads. An air-tight connector should be used to prevent air leakages between the furnace and the recuperator.

Thermal expansion is the big problem of a recuperator. For a conventional shell and tube heat exchanger configuration, tube expansion tears the tube sheet; hence, a single tube sheet is generally used with suspended open end hot gas feed tubes inside concentric closed end suspended outside tubes. The thermal expansion problem is exacerbated by the much higher heat transfer to the front row of tubes (shock tubes) because of (a) highest convection ΔT from the hottest (entering) flue gases, (b) gas radiation from the long 'beam' of triatomic gases in the duct approach, and (c) 'solid' radiation from the hot walls of the approach duct [1].

Recuperator damage occurs with the changing of temperature, especially during the furnace on-off period. Tube sheet breakage and tube buckling can occur because of thermal expansion and extraction with the changing of temperature. This problem can be reduced by using an expansion bellows or packing glands for each tube, if temperatures permit. If this equipment becomes work hardened, however, the tube sheet may still be torn.

Direct furnace radiation frequently causes overheating damage, thermal stress damage, within recuperator. The top left view of Figure.5.7 illustrates this problem, and the top right view shows the solution. Damaged or missing recuperator tubes harm operation in two ways:

a) Air leakage from the cold air side to exhaust side may load up the exhaust fans with cold air.
b) Air pressure will drop after the recuperator during high firing, thereby causing a deficiency of air and incorrect furnace atmosphere [28].

Dilution air is often purposely added to the furnace waste gas stream to protect the materials of recuperator and air handling equipment from overheating. Many furnace dilution air systems are undersized by 30 to 50%.

PART 6

SYSTEM MEASUREMENT, ANALYSIS AND ASSESSMENT

The aim of this study is efficient usage of energy within the industry. In this respect, an order of energy efficiency study has been done on an industrial facility reheating furnace and the subject of this thesis is the efficiency and recuperator design for the reheating furnace.

100 t/h capacity rail profile mill reheating furnace was observed by the measurements, efficiency calculations were applied and facility data examined and payback period of investments were determined.

Saving options could be categorized investment required saving options and system enhancements.

Saving options can be categorized like below:

a) Excess air reduction.
b) Prevention of leakage air in recuperator.
c) Observation of combustion and flame length by thermal cameras in the reheating furnace.
d) Reduction of scale loss.
e) Frequency converter appliance for fan motors.
f) Economizer investment.

Investment required saving options were determined as prevention of recuperator air leakages, economizer investment frequency converter appliance for fan motors and insulation of heat lose surfaces. Amount of saving, economical cost of saving, investment costs and payback periods were estimated in Table 6.1.

Table 6.1. Amount of saving, economical cost of saving, investment costs and payback periods.

Saving	Saving Type	Amount of Annual Saving (10^3)		Annually Economical Cost of Saving (USD)	Investment Cost (USD)	Payback Period (Month)
Prevention of leakage air in recuperator.	Energy	23 467 427 390	J	191 726	462 351	29
Economizer investment	Energy	67 919 995 620	J	554 897	102 577	2,3
Reduction of scale loss	Energy + Product	-	-	371 731	330 250	10,7
Frequency converter appliance for fan motors	Electricity	1 531 422 000	J	29 778	14 888	6
Total				**1 148 132**	**910 066**	**Average=12**

6.1. MEASUREMENT PROCEDURE AND INSTRUMENTS

The reheating furnace and recuperator inlet and exit flow properties which are temperature, pressure, velocity and gas chemical composition, were measured to establish the mass and energy balance. The reheating furnace measurement plan is illustrated in Figure 6.1.

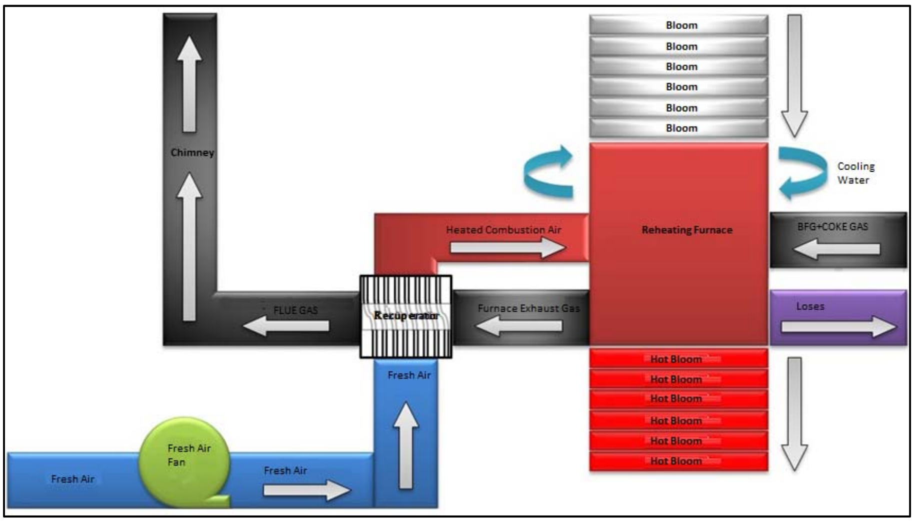


Figure 6.1. Rail profile mill reheating furnace observation and measurement plan.

Coke breeze and blast furnace gas flow rate data is taken from the reheating furnace control panel. Combustion products were calculated by using the coke breeze and blast furnace gas contents. Calculated theoretical values were compared with the measurements from furnace exhaust gas, flue gas analysis, pressure, velocity and temperature to be sure about their correctness.

Flue gas, furnace exhaust gas and recuperator exit gas is measured by electro chemical base working TESTO 350S and TESTO 350 XL model gas analyser. TESTO 445 model measurement device was used to measure flue gas velocity and pressure and then flue gas flow rate was calculated. Percentage of O_2 was designated the combustion air and leakage air flow rates by the measurements from furnace exit and chimney.

6.2. ASSESSMENT OF MEASUREMENT AND CALCULATION RESULTS

The reheating furnace measurements provided data about system boundary conditions such as combustion gas product content, flow rate, velocity, pressure and temperature. By using these data mass and energy balance equations were generated. As a result, main efficiency loses were determined like below:

a) Combustion with high rate excess air.
b) Leakage air in recuperator.
c) Flue gas loses.
d) Excess scale formation.

6.2.1. Reheating Furnace Measurement Results

The reheating furnace recuperator inlet and exit oxygen rate, exhaust gas temperature measurement and fuel flow rate values are given in Table 6.2.

Table 6.2. Rail profile mill reheating furnace recuperator inlet and exit measurement data and fuel flow rates.

Reheating Furnace		
	O_2 (%)	Temperature (K)
Recuperator Inlet	6,25	866
Recuperator Exit	8,5	608
Coke breeze (Nm^3/s)	1,288	
Blast Furnace Gas (Nm^3/s)	0,161	

Blast furnace gas and coke breeze, are burned in the reheating furnace after mixing certain rates, analysis values are given in Table 6.3 and 6.4.

Table 6.3. Rail profile mill reheating furnace fuel blast furnace gas analysis data.

Fuel Composition (mass %)	CO_2	CO	H_2	CH_4	Inert	Lower Heating Value (J/kg)	Higher Heating Value (J/kg)
Original base	18,64	23,17	2,08	0	56,11	3 152 660	3 194 530

Table 6.4. Rail profile mill reheating furnace fuel coke breeze analysis data.

Fuel Composition (mass %)	CO_2	C_2H_4	O_2	CO	H_2	CH_4	C_2H_6	C_2H_2	Inert	Lower Heating Value (J/kg)	Higher Heating Value (J/kg)
Original base	3,01	1,62	0,37	6,68	57,75	22,28	0,62	0,11	7,56	16 750	18 930

Fuel rate, furnace combustion gas oxygen rate and composition analysis data were used to determine the combustion product content and percentage of products. Combustion product information is given in Table 6.5 and Table 6.6.

Table 6.5. Rail profile mill reheating furnace fuel blast furnace gas, combustion products, and flow rate data.

Fuel			**Combustion Products (Nm^3/s) (10^{-3})**						
Fuel Analysis	**% (ob.)**	**Stoichiometric O_2 (10^{-3})**	**CO_2**	**SO_2**	**N_2**	**Argon**	**H_2O**	**O_2**	**Others**
CO_2	18,64	0	30,030	0	0	0	0	0	0
CO	23,17	18,663	37,355	0	69,563	0,827	1,633	0	0,008
H_2	2,08	1,677	0,002	0	6,244	0,075	3,497	0	0
N_2	56,11	0	0	0	90,4	0	0	0	0
Inert	0	0	0	0	0	0	0	0	0
Total	**100**	**20,34**	**67,388**	**0**	**166,208**	**0,902**	**5,13**	**0**	**0,008**
Excess Air			0,03	0	80,177	0,955	1,883	21,513	0,011
Gas Composition % (ob.)			**19,59**	**0**	**71,58**	**0,54**	**2,04**	**6,25**	**0,01**

Table 6.6. Rail profile mill reheating furnace fuel coke breeze, combustion products and flow rate data.

Fuel			**Combustion Products (Nm^3/s) (10^{-3})**							
Fuel Analysis	**% (ob.)**	**Stoichiometric O_2 (10^{-3})**	**CO_2**	**SO_2**	**N_2**	**Argon**	**H_2O**	**O_2**	**Inert**	**Others**
CO_2	3,01	0	38,769	0	0	0	0	0	0	0
C_2H_4	1,62	62,6	41,822	0	233,305	2,777	47,211	0	0	0,03
O_2	0,37	-4,766	0	0	-17,761	-0,211	-0.211	0	0	-0,002
CO	6,68	43,022	86,102	0	160,338	1,911	3,763	0	0	0,003
H_2	57,75	371,925	0,533	0	1386,155	16,511	776,394	0	0	0,177
CH_4	22,28	573,958	287,8	0	2139,122	25,477	624,175	0	0	0,275
C_2H_6	0,62	27,95	16,011	0	104,172	1,241	26,402	0	0	0,014
C_2H_2	0,11	3,541	2,838	0	13,202	0,158	1,727	0	0	0,003
N_2	6,87	0	0	0	88,488	0	0	0	0	0
Inert	0,69	0	0	0	0	0	0	0	8,888	0
Total	**100**	**1078,23**	473,88	0	4107,027	47,863	1479,46	0	8,888	0,5
Excess Air			0,786	0	2046,838	24,38	48,05	549,197	0	0,261
Gas Composition % (ob.):			5,4	0	70,03	0,82	17,38	6,25	0,1	0,01

Values from Table 6.5 and Table 6.6 were used to calculate total stoichiometric combustion gas, theoretical combustion air, excess air, theoretical total combustion air, furnace exit gas flow rate, excess air rate. Calculated values were compared with furnace exit measurement data. Evaluated results are given in Table 6.7.

Table 6.7. Rail profile mill reheating furnace total combustion air and combustion gas flow rates.

Reheating Furnace Total Combustion Air and Combustion Gas Flow Rates	
Theoretical Flue Gas (Nm^3/s) (ob.)	6,357
Theoretical Combustion Air (Nm^3/s) (ob.)	5,34
Excess Air (Nm^3/s)	2,774
Exhaust Gas Flow Rate (Nm^3/s) (ob.)	9,131
Furnace Air Inlet (Nm^3/s)	8,113
Excess Air Coefficient (%)	51,95

6.2.2. Reheating Furnace Efficiency

Reheating Furnace efficiency was calculated by using the bloom mass flow rate, applied heat on bloom and total fuel mixture heating value data. Obtained results are given in Table 6.8.

Table 6.8. Reheating Furnace Efficiency.

Reheating Furnace Efficiency	
Bloom Mass Flow Rate (m_b, kg/s)	19,325
Applied Heat on Bloom Q_b (J/s)	13 683 671
Total Fuel Mixture Heating Value Q_f (J/s)	22 130 701
General Efficiency (%, Q_s/Q_f)	**61,83**

6.2.3. Amount of Leakage Air in Recuperator

Furnace exhaust gas flow rate, recuperator inlet and exit oxygen gas percentage, and leakage air values in recuperator are given in Table 6.9.

Table 6.9. Rail profile mill reheating furnace recuperator leakage air data.

Amount of Leakage Air in Recuperator	
Flue Gas Oxygen Rate (%)	8,5
Total Furnace Exit Gas Flow Rate (Nm^3/s)	9,131
Total Flue Gas Flow Rate (Nm^3/s)	10,833
Amount of Leakage Air (Nm^3/s)	1,701

6.2.4. Reheating Furnace Energy and Mass Balance

Measured and calculated values were used to establish the reheating furnace and recuperator mass and energy balances. Evaluated results are given in Table 6.10, Table 6.11 and Table 6.12.

Table 6.10. Rail profile mill reheating furnace energy and mass balance.

Reheating Furnace Energy and Mass Balance						
Inlet	**Flow Rate (Nm^3/s)**	**Oxygen (%)**	**Temperature (K)**	**C$_p$ (J/Nm^{3}K)**	**Q (J/s)**	**%**
Blast Furnace Gas (Combustion Heat)	0,161			3 152 660	507,928	1,94
Blast Furnace Gas Sensible Heat)	0,161		308	1 380	7 767,666	0,03
Coke Breeze (Combustion Heat)	1,288			16 747 200	2 157 324	82,51
Coke Breeze (Sensible Heat)	1,288		298	1 350	43 682,277	0,17
Combustion Air (Sensible Heat)	8,113	20,57	591	1 360	3 523 930,706	13,48
Cooling Water	0,14*		297	4 180**	14 039,733	0,05
Bloom	19,679*		328	440**	476 731,144	1,82
Total					**26 145 403**	**100**
Exit	**Flow Rate (Nm^3/s)**	**Oxygen (%)**	**Temperature (K)**	**C$_p$ (J/Nm3K)**	**Q (J/s)**	**%**
Bloom	19,325*		1 350	2 850**	14 160 403,06	54,16
Furnace Exhaust Gas	9,131	6,25%	866	1 570	8 501 656,767	32,52
Cooling Water	0,14*		302	4 180**	16 964,68	0,06
Scale Losses (%1,8 assumed)	0,354*		1 350	680**	259 559,503	0,99
Other Loses (Door and other openness loses, un suitable isolation loses, etc.)					3 206 820,147	12,27
Total					**26 145 403**	**100**

* Kg/s, **J/kg K

Table 6.11. Rail profile mill reheating furnace recuperator energy and mass balance.

Recuperator Energy and Mass Balance						
Inlet	**Flow Rate (Nm^3/s)**	**Oxygen (%)**	**Temperature (K)**	**C_p (J/Nm^3K)**	**Q (J/s)**	**%**
Furnace Exhaust Gas	9,131	6,25	866	1 570	8 501 656,767	97,09
Combustion Air	8,114	20,57	293	1 300	210 760,022	2,41
Leakage Air	1,701	20,57	293	1 300	44 203,302	0,50
Total					8 756 620,094	100,00
Exit	**Flow Rate (Nm^3/s)**	**Oxygen (%)**	**Temperature (°C)**	**C_p (J/Nm^3K)**	**Q (J/s)**	**%**
Flue Gas	10,833	8,50	608	1 430	5 191 905,306	59,29
Combustion Air	8,114	20,57	591	1 360	3 523 930,706	40,24
Loses (Surface Heat)					40 785,244	0,47
Total					8 756 620,094	100,00

Table 6.12. Reheating furnace total energy and mass balance.

System Total Energy And Mass Balance						
Inlet	**Flow Rate (Nm^3/s)**	**Oxygen (%)**	**Temperature (K)**	**C_p (J/Nm^3K)**	**Q (J/s)**	**%**
Blast Furnace Gas (Combustion Heat)	0,161			3 152 660	507 928,619	2,22
Blast Furnace Gas (Sensible Heat)	0,161		308	1 380	7 767,677	0,03
Coke Breeze (Heating Value)	1,288			16 747 200	21 571 324	94,29
Coke Breeze (Sensible Heat)	1,288		298	1 350	43 682,28	0,19
Combustion Air (Sensible Heat)	8,114	20,57	293	1 360	210 760,022	0,92
Cooling Water	0,14*		297	4 180**	14 039,736	0,06
Bloom	19,679*		328	440**	476 731,144	2,08
Leakage Air	1,701	20,57	293	1 360	44 203,303	0,19
Total					22 876 436,79	100,00
Exit	**Flow Rate (Nm^3/s)**	**Oxygen (%)**	**Temperature (K)**	**C_p (J/Nm^3K)**	**Q (J/s)**	**%**
Flue Gas	9,131	8,5	608	1 430	4 376 302,708	19,13
Leakage Air	1,701	8,5	608	1 430	815 602,597	3,57
Bloom	19,325*		1 350	680**	14 160 403,06	61,9
Cooling Water	0,14*		302	4 180**	16 964,680	0,07
Scale Loses Assume (%1,8)	0,354*		1 350	680**	259 559,503	1,13
Other Loses (Door and other openness loses, un suitable isolation loses, etc.)					3 247 604,231	14,2
Total					**22 876 436,79**	**100**

* Kg/s, **J/kg K

Rail profile mill reheating furnace energy balance Sankey diagram is shown in Figure 6.2.

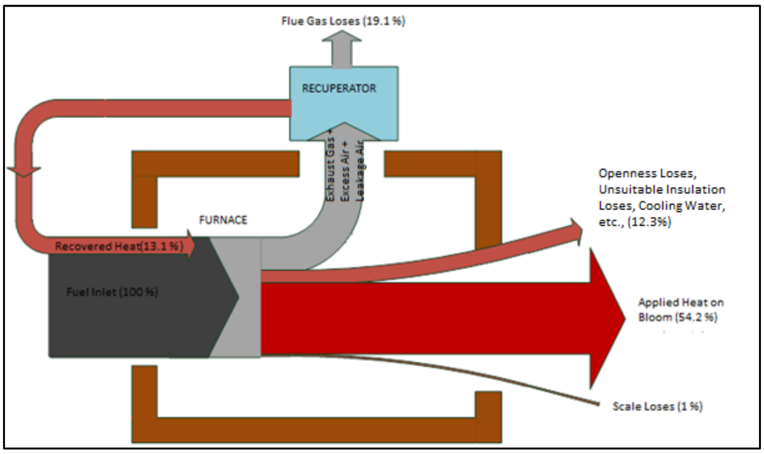


Figure 6.2. Rail profile mill reheating furnace total energy balance Sankey diagram.

6.2.5. Potential Saving Options

a) Excess Air Reduction

Investigations about the reheating furnace designates that optimum combustion is obtained by (38 %) excess air. Measurements showed that rail profile mill reheating furnace was working higher values than optimum excess air values and so high rate of heat was releasing to the environment by flue gas. Reduction of excess air to obtain optimum combustion had a saving potential and this potential was calculated as Table 6.13.

Table 6.13. Reheating furnace excess air reduction saving potential.

Saving Potential by the Reduction of Excess Air	
Excess Air Flow Rate (Nm^3/s)	2,774
Excess Air Ratio (%)	51,95
Optimum Excess Air Ratio (%)	38
C_p (J/Nm^3K)	1 430
Air Flow Rate Reduction(Nm^3/s)	0,745
Air Inlet Temperature (K)	293
Flue Gas Temperature (K)	608
Energy Saving (J/s)	335 698,786
Annual Furnace Operation Time (s) (10^6)	30.6
Annual Energy Saving (J) (10^6)	**10 272 397, 26**

b) Leakage Air Reduction

Recuperator pipe system had failed because of thermal fatigue and oxidation in long period operation and there was air leakage from high pressure region to low pressure one. Leakage air loses was determined the major losing factor on the reheating furnace total efficiency. Saving potential by the prevention of leakage air in recuperator was determined and is shown in Table 6.14.

Table 6.14. Saving potential by the prevention of leakage air in the reheating furnace recuperator.

Saving Potential by the Prevention of Leakage Air	
Leakage Air Flow Rate (Nm^3/s)	1,701
Flue Gas Temperature (K)	608
Ambient Temperature (K)	293
Cp (J/Nm^3K)	1 430
Energy Saving (J/s)	766 908,95
Annual Furnace Operation Time (s) (10^6)	30,6
Annual Energy Saving (J) (10^6)	**23 467 427,39**

c) Investment of Economizer

By using recuperator important portion of flue gas energy can be recovered. However, recuperator exit temperature has important heating potential by the installation of an economizer recovered heat amount is increased and so furnace efficiency is increased. Recovered heat can be used to heat bath water and heating of region in the facility. Energy saving potential by the installation of recuperator is given in Table 6.15.

Table 6.15. Saving potential by the installation of economizer for the reheating furnace.

Saving Potential by the Installation of Economizer	
Exhaust Gas Flow Rate (Nm^3/s)	8,386
Reduction of Excess Air (Nm^3/s)	0,745
Economizer Combustion Gas Flow Rate (Nm^3/s)	8,386
Economizer Inlet Temperature (K)	608
Economizer Exit Temperature (K)	423
C_p (J/Nm^3K)	1 430
Saving Potential (J/s)	2 219 607,597
Annual Furnace Operation Time (s) (10^6)	30,6
Annual Saving Potential (J) (10^6)	**67 919 995,62**

d) Reduction Of Scale Loses

During the reheating operation, hot steel surfaces react with the furnace oxidizing atmosphere resulting in the formation of an iron oxides layer (scale). The yield loss due to this phenomenon depends on furnace operation conditions, i.e. steel temperature, excess combustion air, steel residence time in the furnace, etc., and ranges between 1.5 to 3% of reheated steel.

It has been found that scale formation was most sensitive to oxygen levels in the furnace, steel residence time and temperature. A saving of up to 35 % of steel lost to scale was achieved by reducing the excess air in the furnace from 70% to 20%. Also, longer residence time and higher temperatures of the steel in the furnace resulted in the formation of excessive amounts of scale [41].

Rail profile mill reheating furnace combustion process was occurred by the unsteady flow rate blast furnace gas and coke breeze. Because of this, combustion air flow rate should have been set to obtain complete combustion. Current system was working with 3.7:1 AF ratio. Furnace temperature suddenly decreases, when high AF ratio is fed to furnace. As a result, scale formation and so material lose occurs on the surface of bloom. Rail Profile Mill Facility Engineers specified average rate of scale lose for the plant is about 1.8 %. Investigations designated that these loses could be reduced to 1.5 %. To obtain these coke breeze and blast furnace gas rate should be measured by automation and AF ratio should be regulated by this automation.

Saving potential by the reduction of scale formation on rail profile mill reheating furnace:

Mill exit product average unit cost = 1,25 ₺ /kg

Blast Furnace ore inlet unit cost = 0,58 ₺/ kg

Rail profile mill production objective = 280×10^6 kg/year

Saving potential = (Mill exit product average unit cost - Blast Furnace ore inlet unit cost) x (0.003 x annual production objective) = (1,25 – 0,58) x (0.003 x 280×10^6) =562800 ₺/year

e) Total Saving Potential

Total saving potential by the appliance of saving methods which are discussed above is given in Table 6.16.

Table 6.16. Total saving potential of rail profile mill reheating furnace.

Saving	**Energy (J/s)**	**Coal Equivalent (kg/s)**	**Annual Economic Value (USD)**
Reduction of Excess Air	335 698,786	0,014	83 924
Prevention of Leakage Air Loses	766 908,95	0,031	191 726
Economizer Instillation	2 219 607,597	0,09	554 897
Reduction of Scale Loses	-	-	371 731
Total	**3 322 216,497**	**0,136**	**1 202 278**

1 kg Coal = 24 480 220 J/kg = 0, 20 USD

6.2.6. Investments and Payback Periods

Reduction of excess air is discussed above doesn’t need any investment. Prevention of leakage air, economizer installation and reduction of scale loses need investment. In Table 6.17 shows the costs of investments and payback periods.

Table 6.17. Rail profile mill reheating furnace investments and payback periods.

Saving	**Investment**	**Investment Cost (USD)**	**Saving (USD)**	**Payback Period**
Reduction of Excess Air	-	-	83.924	-
Prevention of Leakage Air Loses	Recuperator Replacement	462.351	191.726	29 month
Economizer Installation	Economizer Installation	102.577	554.897	2,3 month
Reduction of Scale Loses	Fuel Composition Online Control and PLC integration	330.250	371.731	10,7 month

6.2.7. Achievable Efficiency Value of the System by the Appliance of Saving Methods

By the appliance of saving methods which are discussed above could be achieved efficiency value is given in Table 6.18.

Table 6.18. Achievable efficiency value of the reheating furnace by the appliance of saving methods.

Reheating Furnace Efficiency by the Appliance of Saving Methods	
Saving Energy (J/s)	3 322 216,497
Applied Heat on Bloom After Saving Q_b (J/s)	17 005 888,42
Total Fuel Heat Q_f (J/s)	22 130 701,41
General Efficiency (%, Q_b/Q_f)	**76,8**

Table 6.18 designates that by the appliance of saving methods achievable efficiency is increased from 61.83% to 76.8%.

Figure 6.3 shows the achievable energy balance Sankey diagram by the application of saving methods on rail profile mill reheating furnace. In the illustration available minimum flue gas lose estimated 6,8% by the application of an economizer at the exit of recuperator.

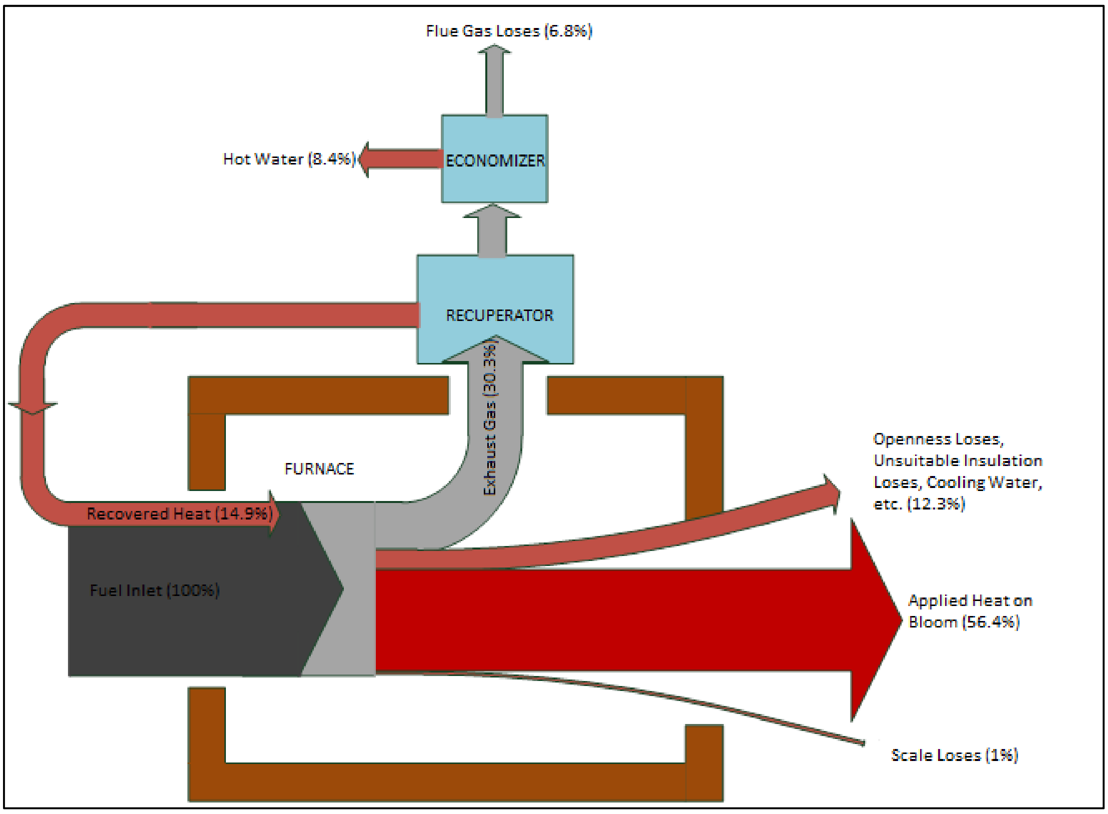


Figure 6.3. By the appliance of saving methods achievable energy balance Sankey diagram of rail profile mill reheating furnace.

PART 7

RECUPERATOR DESIGN, PRODUCTION AND ASSEMBLY

Rail profile mill reheating furnace etude showed the necessity of the design of a new recuperator. Operating system recuperator had been punctured by the oxidative exhaust gas in short period because of its low corrosion resistance. Leakage in a recuperator mean low temperature air is heated and released to the environment and so heat loses occurs. Low temperature combustion air leaks from one domain to another and carries the heat to the environment. This causes the lower system efficiency. In the same manner fuel consumption is increased to optimize the combustion and as a result emission of the exhaust gas increases. A new high temperature and corrosion resistant recuperator was designed and assembled to the system.

7.1. RECUPERATOR DESIGN PARAMETERS

Instead of existing recuperator, a new recuperator which has the properties are 40500 Nm^3/h exhaust gas capacity, 33400 Nm3/h combustion air capacity, combustion air exit temperature is maximum 575 ^oC design, production and assembly was decided. The goals of new design are reduction of fuel consumption about 12%, 12% lower exhaust emission and about 10 year recuperator service life.

Recuperator Design Parameters:

Recuperator design parameters are chosen to obtain optimum performance, maximum service life, optimum material cost, minimum machining operation, working conditions and especially maximum effectiveness from the design. Maximum working load conditions should be taken into account and safe working range should be estimated for the designed product. Estimated design parameters are given in Table 7.1.

Table 7.1. Recuperator design parameters.

Design Parameters			
	Normal	**Maximum**	**Unit**
Exhaust Gas Flow Rate	11,25	13,22	Nm^3/s
Exhaust Gas Inlet Temperature	1 093	1 123	K
Exhaust Gas Pressure Drop	107,87	156,9	Pa
Combustion Air Flow Rate	9,277	10,888	Nm^3/s
Combustion Air Inlet Temperature	293	298	K
Combustion Air Exit Temperature	848	853	K
Combustion Air Pressure Drop	2 745,68	3 726,28	Pa

7.2. THERMAL ANALYSIS

$$c_{p_a} = 1008 \frac{J}{kgK} \tag{7.1}$$

$$c_{p_f} = 1100 \frac{J}{kgK} \tag{7.2}$$

$$\dot{m}_a = 11{,}95 \frac{kg}{s} \tag{7.3}$$

$$\dot{m}_f = 16.65 \frac{kg}{s} \tag{7.4}$$

$$\dot{Q}_a = \dot{m}_a * c_{p_a} * \left(T_{e_a} - T_{i_a}\right) \tag{7.5}$$

$$\dot{Q}_a = 11.95 * 1008 * (575 - 20) = 6685308\, W \tag{7.6}$$

$$\dot{Q}_f = \dot{m}_f * c_{p_f} * \left(T_{i_f} - T_{e_f}\right) \tag{7.7}$$

$$\dot{Q}_a = \dot{Q}_f = 6685308 = 16.65 * 1100 * (820 - T_{e_f}) \tag{7.8}$$

$$T_{e_f} = 455°C \tag{7.9}$$

$$\Delta T_m = \frac{\sqrt{(T_{i_f} - T_{e_f})^2 + (T_{e_a} - T_{i_a})^2}}{\ln\left[\frac{\left(T_{i_f} + T_{e_f}\right) - \left(T_{i_a} + T_{e_a}\right) + \sqrt{(T_{i_f} - T_{e_f})^2 + (T_{e_a} - T_{i_a})^2}}{\left(T_{i_f} + T_{e_f}\right) - \left(T_{i_a} + T_{e_a}\right) - \sqrt{(T_{i_f} - T_{e_f})^2 + (T_{e_a} - T_{i_a})^2}}\right]} \tag{7.10}$$

$$\Delta T_m = \frac{\sqrt{(820 - 455)^2 + (575 - 20)^2}}{\ln\left[\frac{(820 + 455) - (20 + 575) + \sqrt{(820 - 455)^2 + (575 - 20)^2}}{(820 + 455) - (20 + 575) - \sqrt{(820 - 455)^2 + (575 - 20)^2}}\right]} \tag{7.11}$$

$$\Delta T_m = 148℃ \tag{7.12}$$

$$Q = U * A * \Delta T_m \tag{7.13}$$

$$\frac{1}{U} = \frac{1}{h_a} + \frac{1}{h_f} + \frac{d_o \ln\left(\frac{d_o}{d_i}\right)}{2 * k_{ow}} \tag{7.14}$$

Chosen special material tube available standard size and existing recuperator dimensions suggests the tube specifications for design as $d_o = 42.7mm, t = 3mm, k_{ow} = 20\frac{W}{mK}$

$$h_a = 12.58 * c_{p_a} * \frac{{G_a}^{0.8}}{(d_i)^{0.2}} \tag{7.15}$$

$$G_a = 21.73 \frac{kg}{sm^2} \tag{7.16}$$

$$h_a = 12.58 * 1.008 * \frac{21.73^{0.8}}{(39.7 * 10^{-3})^{0.2}} \tag{7.17}$$

$$h_a = 283.8 \frac{W}{m^2K} \tag{7.18}$$

$$h_f = 1.1 * (h_c + h_{rg}) \tag{7.19}$$

$$h_c = 0.018 * C_{p_f} * \frac{(G_f)^{\frac{2}{3}} * (T_{avg})^{0.3}}{(d_o)^{\frac{1}{3}}} \tag{7.20}$$

$$G_f = 2.43 \frac{kg}{sm^2} \tag{7.21}$$

$$C_{p_f} = 1.0775 + 1.1347 + 3.157 * 10^{-4} * T_{avg} \tag{7.22}$$

$$C_{pa_f} = 1.0775 + 1.1347 + 3.157 * 10^{-4} * 910 = 2500 \frac{J}{kgK} \tag{7.23}$$

$$h_c = 0.018 * 2.5 * \frac{(2.43)^{\frac{2}{3}} * (910)^{0.3}}{(42.7 * 10^{-3})^{\frac{1}{3}}} \tag{7.24}$$

$$h_c = 1.8 \frac{W}{m^2K} \tag{7.25}$$

$$h_{rg} = 9.2 * 10^{-2} * T_{avg} - 34 \tag{7.26}$$

$$h_{rg} = 9.2 * 10^{-2} * 910 - 34 \tag{7.27}$$

$$h_{rg} = 50\frac{W}{m^2K} \tag{7.28}$$

$$h_f = 1.1 * (1.8 + 50) \tag{7.29}$$

$$h_f = 57\frac{W}{m^2K} \tag{7.30}$$

$$\frac{1}{U} = \frac{1}{283.8} + \frac{1}{57} + \frac{42.7 * 10^{-3} \ln\left(\frac{42.7}{39.7}\right)}{2 * 20} \tag{7.31}$$

$$U = 47.3\frac{W}{m^2K} \tag{7.32}$$

$$Q = 6685 * 10^3 = 47.3 * A * 148 = 47.3 * A * 148 \tag{7.33}$$

$$A = 954m^2 \tag{7.34}$$

$$N = \frac{A}{A_p} = \frac{954}{\pi * 42.7 * 10^{-3} * 3.086} \tag{7.35}$$

$$N = 2304\ (tubes) \tag{7.36}$$

7.3. RECUPERATOR PIPE MATERIALS

Recuperator inlet and exit conditions has high level temperature difference, there is high temperature inlet and lower temperature exit. Recuperator design was carried out by using four orders different tube material to satisfy the thermal, operational and economical design considerations. Chosen tube properties and comparison with existing recuperator is given in Table 7.2.

Table 7.2. Recuperator tube properties and comparison with existing recuperator.

	Existing Recuperator Tube Specifications								**New Recuperator Tube Specifications**							
Number of Tubes									X10CrAlSi25 (SIC12)	2 × (32 × 7) = 448 Pcs						
	DIN 1.4742								X10CrAlSi18 (SIC10)	2 × (32 × 11) = 704 Pcs						
	DIN 1.4724	2 × (24 × 2) = 96 Pcs							X10CrAlSi13 (SUS410L)	2 × (32 × 7) = 448 Pcs						
	DIN 1.4720	2 × (24 × 12) = 576 Pcs														
	ST 37	2 × (24 × 15) = 720 Pcs							STB340							
									S-TEN	2 × (32 × 11) = 704 Pcs						
Total Pieces	Ø 44,5 / 1392 Pcs								Ø 42,7 / 2304 Pcs							
Chemical Composition of Tubes		C	Si	Mn	P	S	Cr	Others		C	Si	Mn	P	S	Cr	Others
									X10CrAlSi25	≤0,12	1,2-1,5	≤1,0	≤0,045	≤0,03	23-25	1,2-1,7 (Al)+ Ti
									X10CrAlSi18	≤0,12	0,7-1,2	≤1,0	≤0,045	≤0,03	17-19	0,7-1,2 (Al)+Ti
	DIN 1.4724	≤0,12	0,7-1,4	≤1,0	≤0,04	≤0,03	12-14	0,7-1,2 (Al)	X10CrAlSi13	≤0,03	≤1,0	≤1,0	≤0,04	≤0,03	11-13	
	DIN 1.4720															
	ST 37	≤0,17			≤0,04	≤0,04		≤0,009(N)	STB340							
									S-TEN	≤0,14	≤0,55	≤0,7	≤0,025	≤0,025		
Tube Thickness	2,6 mm								3 mm							
Total Weight	8.650 kg × 2 Units = 17.300 kg								16.000 kg × 2 Units = 32.000 kg							

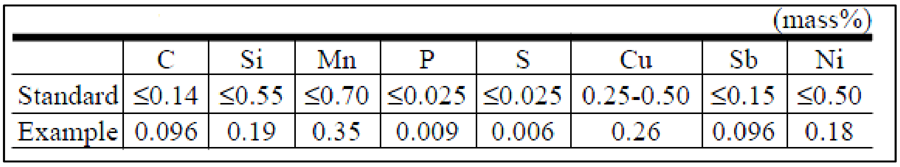
7.3.1. Sulphuric Aside Corrosion Resistant S-TEN Series Steel Tubes

Combustion of sulphur containing fuels forms SO_3 in exhaust gas. When exhaust gas temperature drops to below a dew point or when the gas is in contact with a low-temperature wall, SO_3 and H_2O, contained in the gas, are combined to form highly-concentrated sulphuric acid (H_2SO_4) that corrodes steel. This is sulphuric acid dew corrosion, which severely corrodes not only carbon steel but also stainless steel unlike normal atmospheric corrosion [41]. S-TEN series steel has the perfect corrosion resistance properties and used for high temperature applications like, heat exchangers, chimneys, power plant high corrosive region applications. Additionally, with the intention of applying this steel not only to no pressure sections but also to pressure sections, such as fuel economizers. Nippon Steel has obtained a permit to use this material based on “Technical standards for thermal power plants by Ministry of Economy and Trade and Industry (METI),” in 2001. This material was standardized as material “KA-STB380J1” in May, 2002 [41].

a) Chemical Composition of S-TEN Tubes

Chemical composition of S-TEN series Tubes are given in Table 7.3.

Table 7.3. Chemical composition of S-TEN series tube [41].



(mass%)

	C	Si	Mn	P	S	Cu	Sb	Ni
Standard	≤0.14	≤0.55	≤0.70	≤0.025	≤0.025	0.25-0.50	≤0.15	≤0.50
Example	0.096	0.19	0.35	0.009	0.006	0.26	0.096	0.18

b) Workability of S-TEN Tubes

S-TEN steel could be welded with ordinary steel on the same strength level; it doesn’t contain alloy elements, like chromium, and contains low carbon. Tensile test results indicate that tubes were connecting-welded with each other, and the tube was ruptured surprisingly at the position of the base material, indicating good weld strength.

c) Corrosion Resistance of S-TEN Tubes

S-TEN exhibits the best resistance to sulphuric acid and hydrochloric acid (HCl) dew corrosion found in the flue gas treatment e$_q$uipment used with coal fired boilers, waste incineration plants, according to surveys conducted by Nippon Steel [42].
The tube type air preheater of a heavy oil-fired boiler is the typical equipment attacked by sulphuric acid dew corrosion. Generally, this corrosion is more severe on the low temperature side. Two kinds of tubes, S-TEN 1 and carbon steel STB340-EG were arranged in the front row of a tube type air preheater.

Table 7.4 shows the results of investigation how they were corroded by extracting part of them after one year. The tubes are so structured that they contact combustion exhaust gas inside and preheated air outside. The estimated volume of corrosion of S-TEN 1 tube in one year was 0.04 mm to 0.22 mm, about 1/5 of 0.46 to 1.13 mm in the ordinary steel tube. The corrosion products inside the tube were composed mainly of $FeSO_4$ - H_2O and $FeSO_4$ - $4H_2O$, peculiar to sulphuric acid dew corrosion. This induces us to think that they were in the sulphuric acid dew corrosion environment. The foregoing results reveal that S-TEN 1 tube is excellent in the resistance to sulphuric acid dew corrosion [41].

Table 7.4. Results of actual tube tests of S-TEN 1 tubes [41].

	Measured value of corrosion thinning (m/172800s)		**Estimated Annual Corrosion Volume (m/y) (10^{-3})**
Kind of Steel	**Maximum**	**Average**	
S-TEN 1	0,12	0,02	0,04-0,22
STB340	0,62	0,25	0,46-1,13

d) Resistance to Hydrochloric Acid Dew Corrosion

The dew-point temperature of hydrochloric acid is lower than that of sulphuric acid, and considered to be lower than 72˚C. In the exhaust gas system of a waste incineration facility, hydrochloric acid dew corrosion sometimes occurs as exhaust gas temperature goes lower after improvement work for anti-dioxin measures. Figure

7.1 shows the respective resistances of various kinds of steel materials. It is apparent that S-TEN 1 (added Cu, Sb) tube is more excellent in resistance to hydrochloric acid than other sulphuric acid resistant steel (added Cu, high Cr) tubes [41].

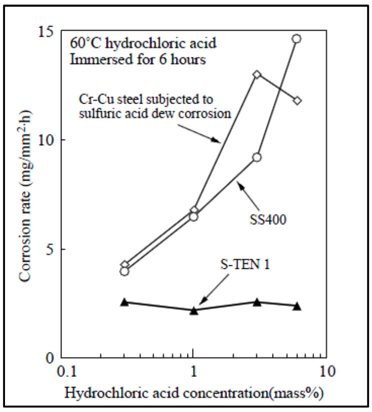
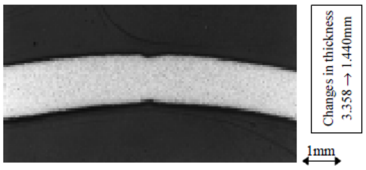


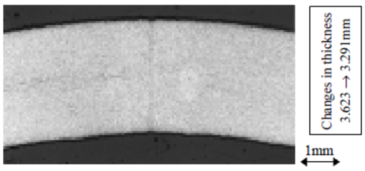
Figure 7.1. Resistance to hydrochloric acid of S-TEN 1 steel [41].

e) Acid Resistance of Weld Portion of ERW Tube

Test pieces, divided into half, with weld portions included were sampled from carbon steel tube (STB340) and S-TEN 1 tube, and immersed in a test solution of 40% H_2SO_4 at 60˚C. Figure 7.2 shows how they were corroded after the immersion. Carbon steel tube STB340 was thinned by about 40%. However, S-TEN 1 ERW tube showed almost no trace of thinning with no selective corrosion observed at the weld portion [41].



(a) ERW carbon steel (STB340) tube (after 4 hours)



(b) ERW S-TEN 1 tube (after 6 hours, 5 cycles)

Figure 7.2. Macro-structure after test of immersion in sulphuric acid at gas liquid equilibrium state of sulphuric acid-water system [41].

7.3.2. SIC Series Oxidation Resistant Stainless Steel Seamless Tube

SIC series, SIC9, SIC10 and SIC12, has an excellent resistance against to oxidation and vanadium or sulphur attack because of its high content of silicon, chromium, and aluminium. Maximum operation temperatures are 900°C for SIC9, 1000°C for SIC10, and 1200°C for SIC12 while working with air.

SIC is applicable for recuperator due to its high oxidation resistance, superior to 18Cr-8Ni austenitic stainless steel. Heat exchange efficiency is improved with high thermal conductivity of the ferritic matrix. SIC series cost is highly competitive due to less Ni content. Typical application areas of SIC series material tubes recuperator are blast furnaces, heating furnaces, glass melting furnaces, lime roasting furnaces [43].

a) Chemical Composition Of SIC Series

Chemical composition of SIC series tubes are given in Table 7.5.

Table 7.5. Chemical composition of SIC series tubes [43].

Chemical Composition (Mass %)							
	C	**Si**	**Mn**	**P**	**S**	**Cr**	**Al**
SIC 9	≤0.12	0.9-1.4	≤1	≤0.045	≤0.03	12-14	0.7-1.2
SIC 10	≤0.12	0.7-1.2	≤1	≤0.045	≤0.03	17-19	0.7-1.2
SIC 12	≤0.12	1.2-1.5	≤1	≤0.045	≤0.03	23-25	1.2-1.7

SIC series tube properties are against the oxidation, vanadium or sulphuric attacks at high temperatures are given in Figure 7.3, Figure 7.4 and Figure 7.5 [43].

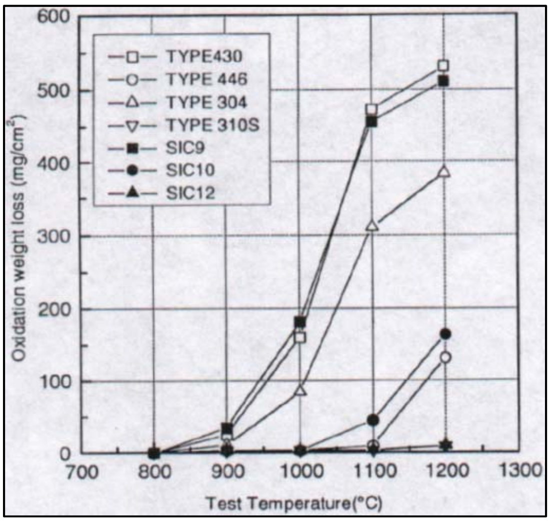


Figure 7.3. SIC series oxidation resistance [43].

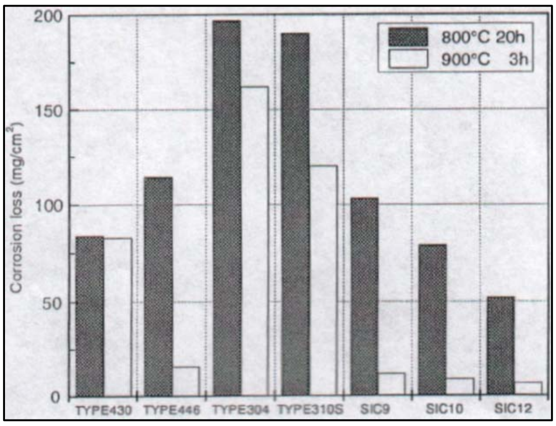


Figure 7.4. Comparison of different steels against the vanadium [43].

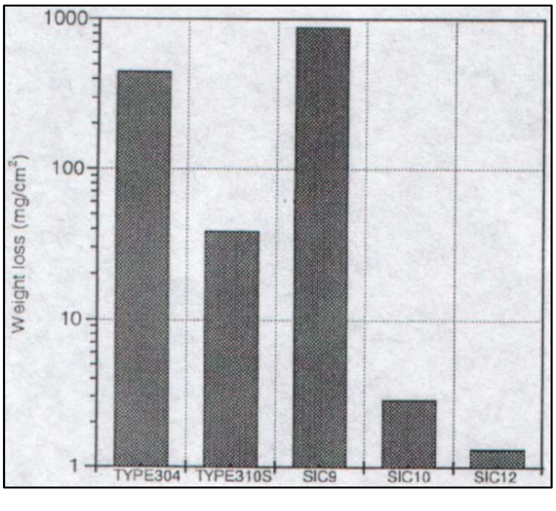


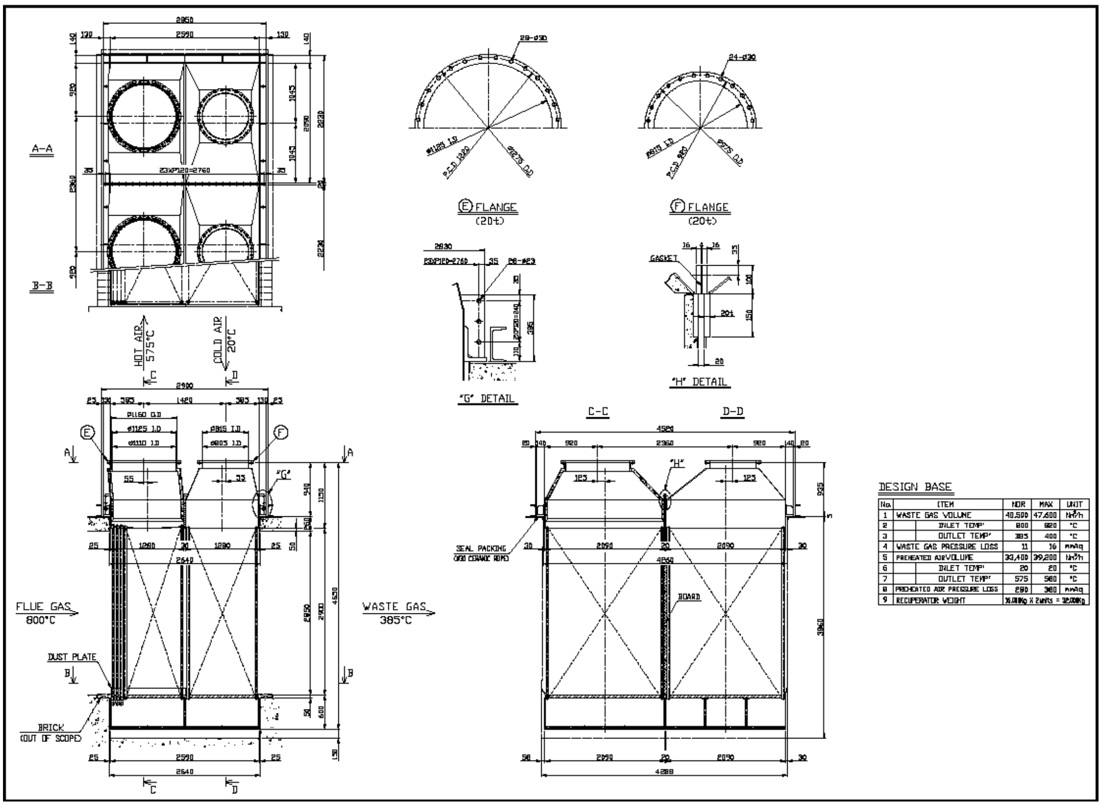
Figure 7.5. Corrosion loses after 50 hours 950°C flue gas exposure [43].

PART 8

COMPUTER AIDED DESIGN AND ANALYSIS OF RECUPERATOR

8.1. COMPUTER AIDED DESIGN

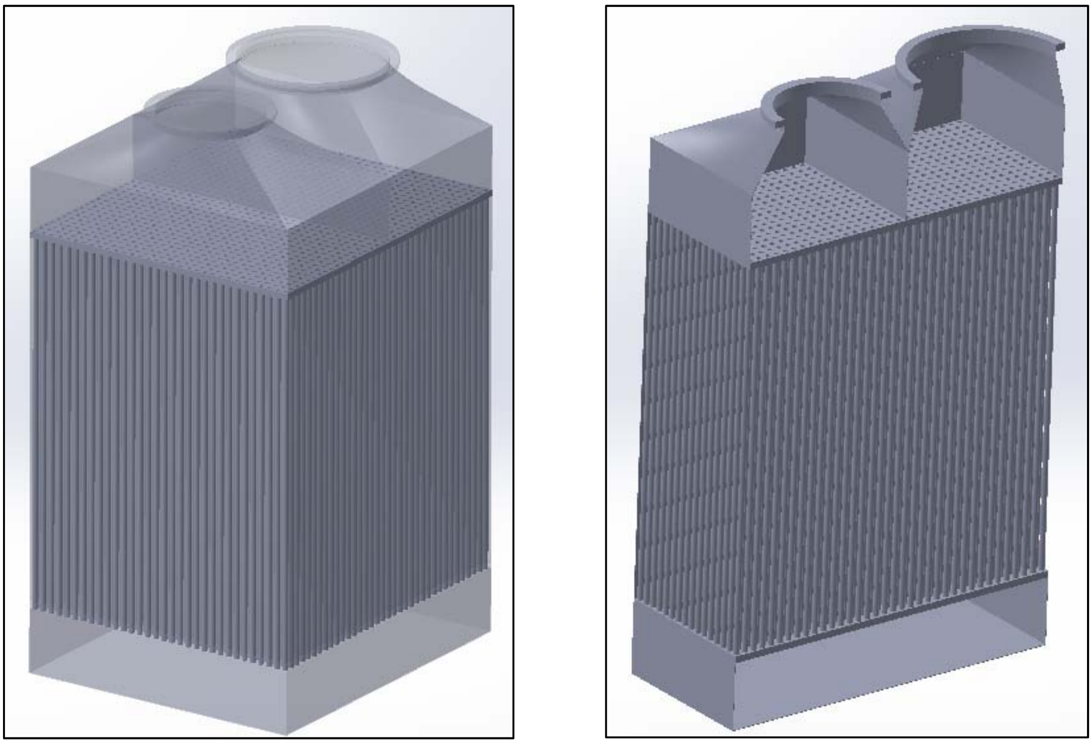
Design of the recuperator with software was done after the determination of theoretical estimations. Computer aided design of recuperator was done by Solidworks software and design technical drawings were given in Figure 8.1 and Figures 8.2.



DESIGN BASE

No.	ITEM	NOR	MAX	UNIT
1	WASTE GAS VOLUME	40,500	47,600	Nm³/h
2	INLET TEMP'	800	820	°C
3	OUTLET TEMP'	385	400	°C
4	WASTE GAS PRESSURE LOSS	11	16	mmAq
5	PREHEATED AIR VOLUME	33,400	39,200	Nm³/h
6	INLET TEMP'	20	20	°C
7	OUTLET TEMP'	575	580	°C
8	PREHEATED AIR PRESSURE LOSS	280	380	mmAq
9	RECUPERATOR WEIGHT	16,000Kg X 2units = 32,000Kg		

Figure 8.1. 2D technical drawing of recuperator [44].



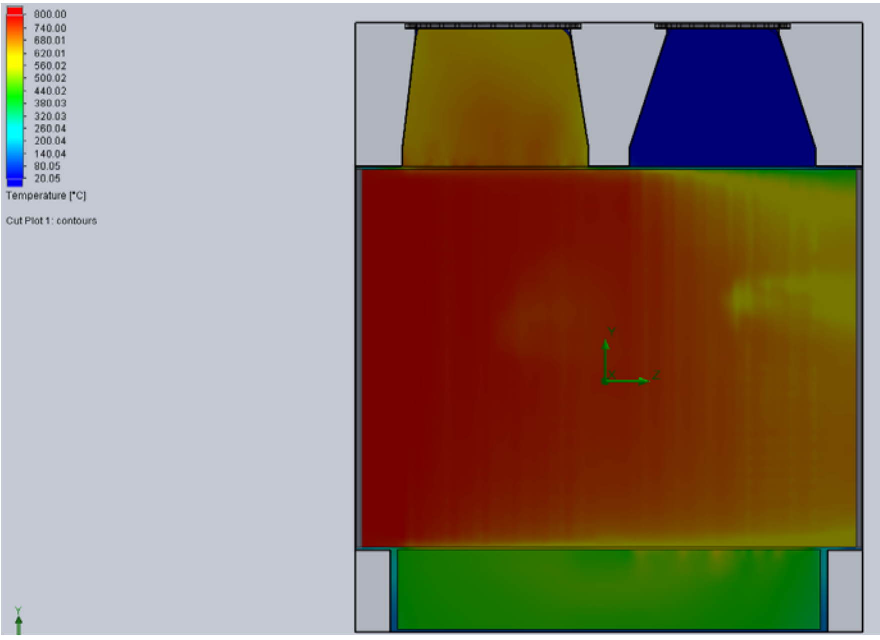
a) 3D Recuperator assembly. b) Section view of recuperator.

Figures 8.2. 3D Views of assembled recuperator.

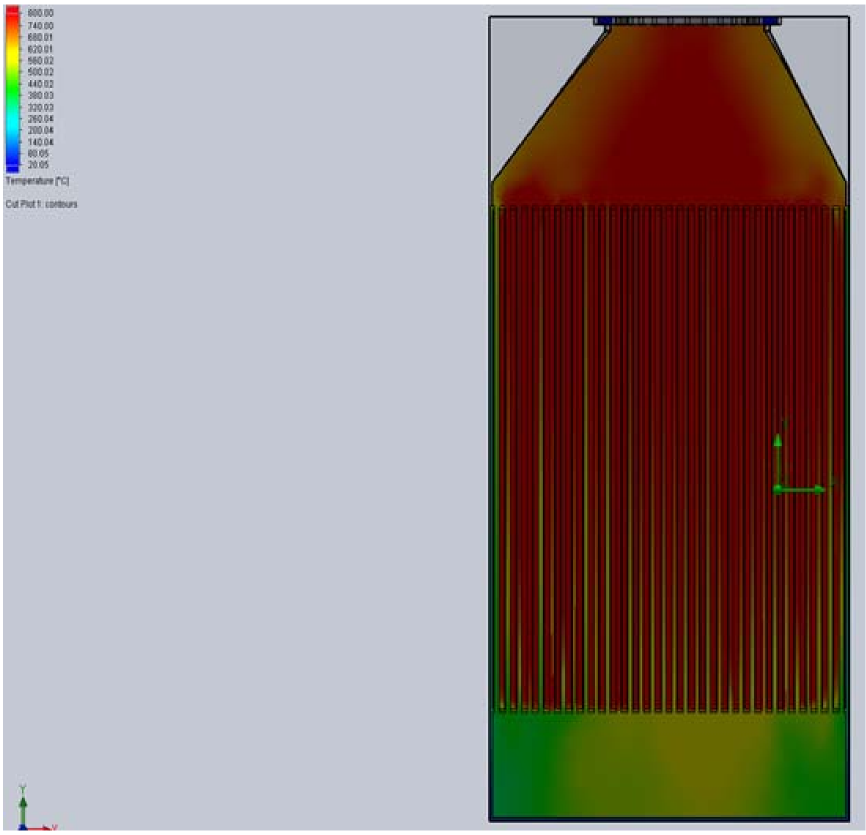
8.2. DESIGNED RECUPERATOR ANALYSIS

Recuperator design had been completed and analysis was applied by using Solidworks Flow Simulation Software. While furnace exhaust gas was flowing out of the recuperator tubes, combustion air gas was flowing in the tubes. By the application of analysis temperature distribution of recuperator is given in Figures 8.3.

Combustion air inlet temperature is 20^{o}C and exit is about 590^{o}C and furnace exhaust gas enters the recuperator about 800^{o}C and exit between 400 and 475 ^{o}C.



a) Temperature distribution



b) Temperature distribution

Figures 8.3. Temperature distribution in the recuperator

Flow trajectories in the recuperator are shown in Figure.8.4 and Figure.8.5.

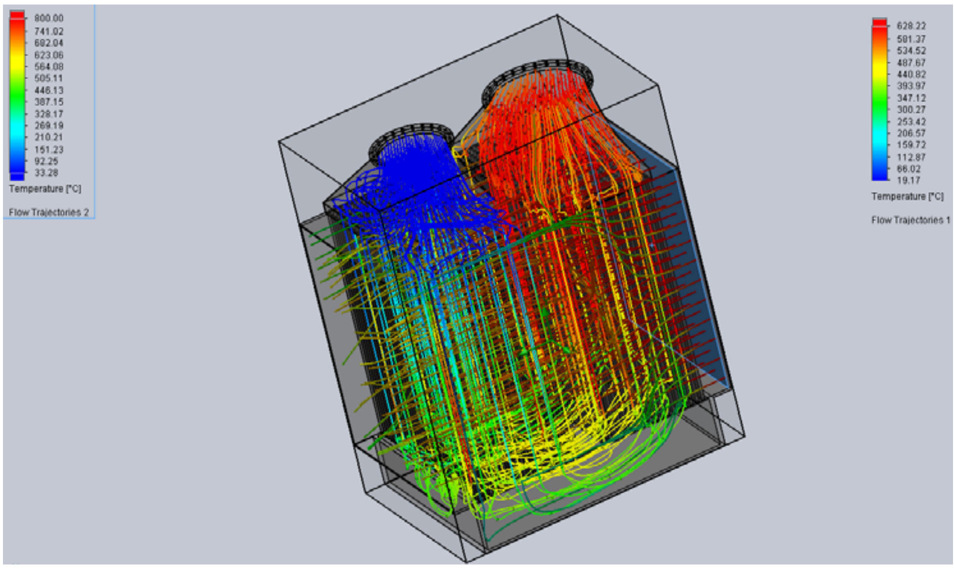


Figure 8.4. Combustion air and flue gas flow trajectories in the recuperator.

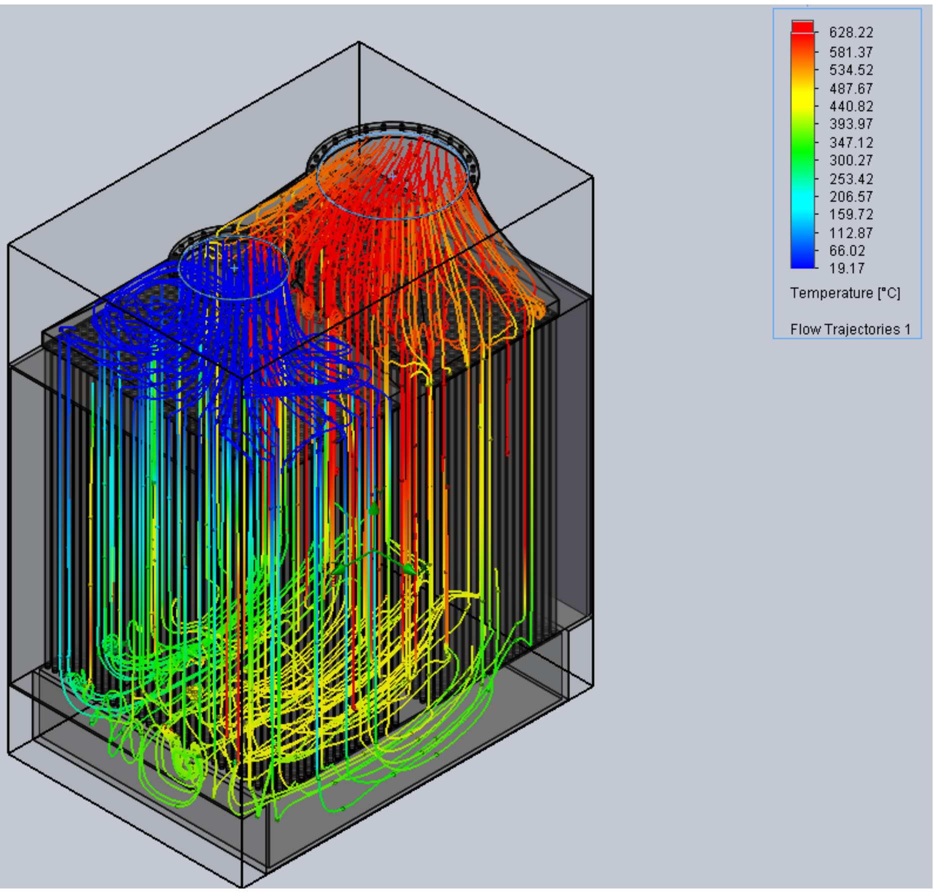


Figure 8.5. Combustion air flow trajectories in the recuperator.

PART 9

RESULTS AND DISCUSSION

9.1. RECUPERATOR PRODUCTION AND ASSEMBLY

Finally recuperator has been produced and assembled by the changing of existing recuperator. Leakage tests were applied after the assembly operation and results are shown in Table 9.1.

Table 9.1. Leakage test results of new recuperator.

Leakage method	**Leakage Time**	**Test Method**	**Test Result**
Spray	5 min.	Removing by solvent	No leakage was observed

New recuperator inlet and exit conditions were measured after the assembly process and measurement results are given in Table 9.2.

Table 9.2. New recuperator inlet and exit conditions measurement results.

Furnace Exhaust Gas Temperature	**Recuperator Exit Temperature**	**Combustion Air Inlet Temperature**	**Combustion Air Exit Temperature**
925 K	656 K	296 K	706 K

Measurement results, operation automation system results of the rail profile mill reheating furnace, and software analysis supported to the theoretical base estimations. Furnace boiler combustion efficiency, combustion control, energy recovery has been obtained and product quality improved. By the energy recovery fuel consumption has been decreased. Environmentally, Releasing heat has been decreased and by the complete combustion unburned carbon content in the exhaust gas of rail profile mill reheating furnace has been reduced.

Assembly region, assembly operation and destroyed recuperator pictures is given in Figures 9.1.

a) Recuperator assemble region.

b) New recuperator assembly

c) Destroyed recuperator.

Figures 9.1. New recuperator assembly.

PART 10

SUMMARY AND CONCLUSION

An industrial facility rail profile mill reheating furnace efficiency analysis, fuel optimization, a new recuperator, is high corrosion resistant, highly efficient, design, production and assembly has been done in order to recover energy from high temperature (700~850^{o}C) flue gas, and so increase the efficiency of the reheating furnace and save energy. By the assembly of the new recuperator required combustion air temperature for the reheating furnace has been increased from 375°C to 575°C and so energy efficiency of the system has been increased. By the increase of energy efficiency and complete combustion has enhanced product quality and decreased production costs. Complete combustion means minimum amount of unburned carbon content in the flue gas and so lower carbon emission. Additionally, higher efficiency refers to the lower fuel consumption and lower emission too. New recuperator has longer service life and has a different design. In the first three pipe order has damper to damp the expansion and so it doesn't need backbone configuration.

Recuperator exit flue gas temperature is about 400°C and yet has a heating potential. In this respect, an economizer design can be done to obtain hot water for space heating or sanitary hot water. Thus, the system efficiency can be increased more and more.

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