International Journal of the Physical Sciences Vol. 6(6), pp. 1257-1266, 18 March, 2011
Available online at http://www.academicjournals.org/IJPS
DOI: 10.5897/IJPS10.273
ISSN 1992 - 1950 ©2011 Academic Journals

Full Length Research Paper

Energy, exergy and economic analysis of an annealing furnace

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Accepted 21 February, 2011

Energy efficiency improvements as well as energy savings are the major concern in most of the developed countries all over the world. Furnace is the most common and important part in metal industries. The useful concept of energy and exergy utilization is analyzed to investigate the energy and exergy efficiencies, energy and exergy losses, energy savings and cost benefit of an annealing furnace. The energy and exergy efficiencies of combustor and annealing chamber of the furnace have been analyzed as well. The exergy efficiency of the combustor is found to be 47.1%. The energy and exergy efficiencies of the annealing chamber are found to be 17.7 and 12.9% respectively. The overall energy and exergy efficiencies of the furnace are found to be 16.7 and 7.3% respectively. It is found that the annealing chamber is the major contributor for exergy destruction of about 57% followed by combustion chamber of the annealing furnace. By using a heat recovery system from the flue gas, about 8.1% of fuel can be saved within the payback period of less than 2 months.

Key words: Energy, exergy, efficiency, furnace.

INTRODUCTION

Energy is the most important factor for automation and modernization. Automation and modernization is increasing rapidly in the industrial sectors. The industrial sector is one of the largest consumers of energy in Malaysia (Saidur et al., 2007a; Hasanuzzaman et al., 2008). Energy demand is rising with increasing degree of industrialization and population. The energy demand in Malaysia increased by 203% between 1990 and 2007 whereas the energy demands in industrial sector increased by 262% between 1990 and 2007 (NEBM, 2007). Iron and steel industries is one of the most important sectors in Malaysia. There are 230 companies producing iron and steel products. The Malaysian iron and steel industries cover the primary steel products like direct reduced iron, hot briquetted iron, blooms/slabs and steel billets and a very wide range of downstream flat and long products like hot rolled coils, cold rolled coils, coated steel coils, roofing sheets, steel pipes and sections, steel billets, steel bars, wire rods, wire mesh, hard drawn wires, steel wire ropes, steel wire products, stainless steel pipes and stainless steel wire and fasteners (MIDA, 2010). The fact is that approximately 15% of the world energy production is used in the iron and steel industry (EIA, 2010). Energy cost is about 30% of the total cost element in integrated steel works (Çamdali and Tunç, 2003; Bisio et al., 2000). Furnace is common equipment in metal industries and consumes a significant amount of energy (SMBA, 2010). The blast furnace is the main energy consumer in steel making (Bisio, 1996). Among the various iron and steel plants, furnaces are characterized by very high specific energy consumption (Bisio et al., 2000). Effect of gas temperature on cooling stave of blast furnace was investigated and found that the heat convective coefficient between the furnace shell and environment was 12 W/ (m^2. K) (Xie and Cheng, 2010). Heat transfer in steel making ladle was investigated and found that during steel heating in the ladle furnace, about 83% of heat was not used to heat the steel. These losses are high because of the heat loss in electrodes (cooling system) and heat transfer of the liquid steel from the ladle

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walls (Zimmer et al., 2008). About 36% of total heat input is lost in the furnace (Mohsen and Akash, 1998). By free-burning arcs, 10 to 15% of the energy is transferred to the furnace wall and 5 to 10% to the furnace roof (Bisio et al., 2000).

The first law of thermodynamics refers to the energy analysis which only identifies the losses of energy and effective use of resources. However, the second law of thermodynamics analysis takes the entropy portion into consideration by including irreversibilities (Dincer, 2002). Exergy is a measure of the maximum useful work as in a specified final state in equilibrium with its surroundings. Exergy destruction is a measure of irreversibility that is the source of performance loss (Aljundi, 2009a). It can be highlighted that the potential usefulness of exergy analysis in sectorial energy utilization is substantial and that the role of exergy in energy policy making activities is crucial (Dincer et al., 2004a, b). Application of the second law of thermodynamics is generally preferred in energy analysis, since it gives more correct, reliable and meaningful results (Çamdali et al., 2003). Analysis of the second law of thermodynamics is applied to the ladle furnace by taking liquid steel and stack gas temperatures and production time of liquid steel in the ladle furnace into consideration, actual work, irreversibility and exergy efficiency have been calculated in Turkey. In general, the exergy efficiency is about 50%, and exergy losses cause significant rises in production costs (Çamdali et al., 2001). The energy efficiency was found to be 96% according to the first law although the exergy efficiency was found to be 55% according to the second law in the electric arc furnace. Overall exergy losses in the system were found to be 44.5%. The exergy losses in the electric arc furnaces were caused mainly by chemical reactions and heat transfer (Çamdali and Tunç, 2003). As the iron and steel industry is the largest industrial energy consumer, in order to minimize the energy costs, it is important to determine primary sources of irreversibilities. After locating the primary irreversibility sources, ways of minimizing them can be considered (Çamdali et al., 2001). The usage of coke, natural gas or coal dust as fuels have become so expensive that their efficient utilization is mandatory (Bisio, 1996). With increasing oil prices and higher environmental taxes, many industrial processes can make substantial cost savings by installing a heat recovery system. During the last 15 years, oil prices have been increased to 60 to 70%. Heat recovery gives direct savings in terms of reduction of fuel consumption as well as indirect savings in reducing environmental impact (EHRS, 2010). Application of energy savings option and proper utilization of energy are really important for sustainable industrial development (Saidur et al., 2010c).

Heat recovery systems have been widely used in steel making plants in order to reduce the exhaust gas heat losses. As exhaust gas heat loss accounts for the greatest percentage of thermal loss, furnace efficiency is improved and fuel consumption is reduced (Hasegawa et al., 2000). Annealing is a process in which metals, glass and other materials are treated to render them less brittle and more workable (SMBA, 2010). Annealing furnace is very much common in the metal industry. There are many studies in the literature about the application of the second law in thermal plants. Although, insufficient in quantity, there are some studies regarding the iron and steel sectors (Çamdali et al., 2001). There are very limited works on energy and exergy analysis, and energy savings of annealing furnace in the literature.

The aim of this study is to analyze the energy and exergy efficiency, exergy destruction, energy savings and cost benefits of the annealing furnace.

THEORETICAL BACKGROUND AND MATHEMATICAL FORMULA

This section discusses about the basics of exergy, exergy of fuel, reference environment, several basic equations and mathematical relations for the energy and exergy analysis in the annealing furnace system.

Exergy

From the thermodynamic point of view, exergy is defined as the maximum amount of work which can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment (Dincer et al., 2004b). Exergy can be consumed or destroyed, due to irreversibilities in any real process. The exergy consumption during a process is proportional to the entropy created due to irreversibilities associated with the process.

Exergy of fuel

Exergy of fuel depends on the heating value and specific heat. Exergy of diesel fuel has been calculated by using the higher heating value and specific heat by using Equation (1):

$$\varepsilon_f = h_f - T_0 s_f \tag{1}$$

where higher heating value h_f = 46,100 kJ/kg.K and entropy s_f =2.2 kJ/kg.K (Heywood, 1988)

Chemical exergy

At near ambient conditions, specific exergy of hydrocarbon fuels reduces to chemical exergy and can be written as (Saidur et al., 2010a; Dincer et al., 2004c):

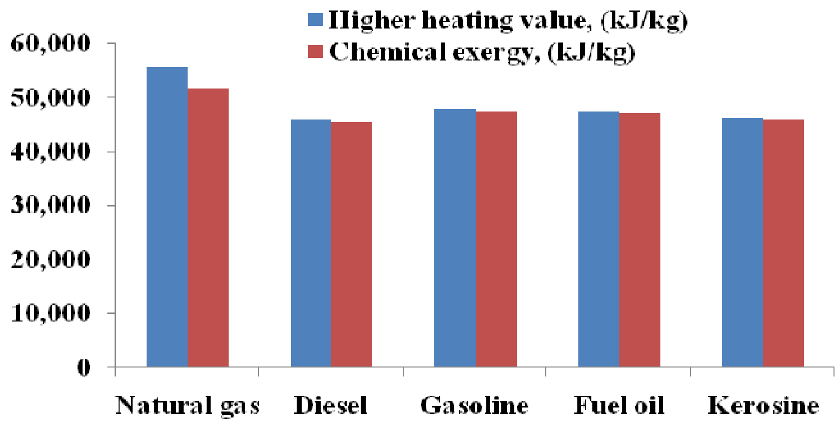

Figure 1. Higher heating value and chemical exergy of fuels (Rosen and Dincer, 1997; Saidur et al., 2007c).

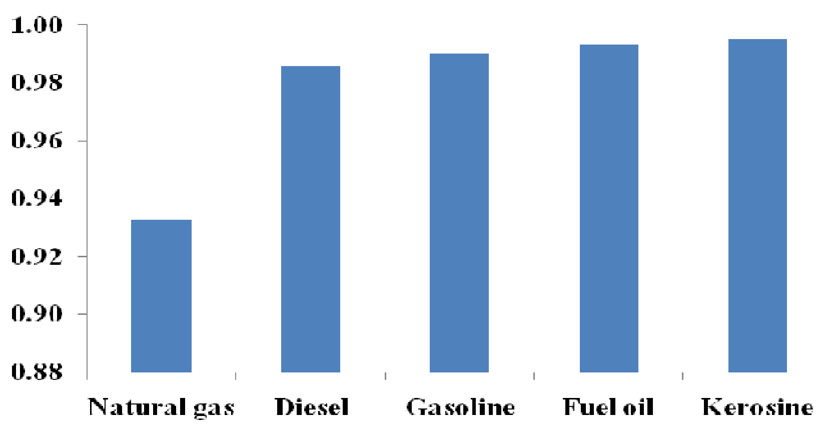

Figure 2. Exergy grade funtion of fuels (Rosen and Dincer, 1997; Saidur et al., 2007c).

$$\varepsilon_{ff} = \gamma_{ff} H_{ff} \quad (2)$$

Where, γ_{ff} denotes the fuel exergy grade function, defined as the ratio of fuel chemical exergy and heating value. Figures 1 and 2 show typical values of H_{ff}, ε_{ff} and γ_{ff} for the fuels encountered in the previous study. Usually, the specific chemical exergy, ε_{ff} of a fuel at T_0 and P_0 is approximately equal to the higher heating value, H_{ff} (Dincer et al., 2004c).

Exergy of hot product and flue gas

Hot product (gas in combustion chamber) and flue gas are the mixture of different gases. The enthalpy and entropy of a mixture are determined by using the partial molar properties (Aljundi, 2009b). The mathematical formula for enthalpy and entropy of the mixture can be written as follows:

$$h = \sum N_i h_i \quad (3)$$

$$s = \sum N_i s_i \quad (4)$$

Exergy of the hot product and flue gases are calculated by using the enthalpy and entropy of the individual gases.

Energy and exergy balances

Energy and exergy balances for an unsteady flow process in a system during a finite time interval can be written as (Dincer and Rosen, 2007; Dincer et al., 2004c; Saidur et al., 2007a, c):

Table 1. Data of an annealing furnace.

Substance	Mass flow rate (kg/s)	Temperature (℃)
Air	0.165	25
Fuel	0.011	25
Hot Product	0.176	1250
Flue gas	0.176	390

Energy input – Energy output = Energy accumulation (5)

Exergy input – Exergy output – Exergy consumption = Exergy accumulation (6)

Equations 5 and 6 demonstrate an important difference between energy and exergy; energy is conserved, while exergy is consumed due to irreversibilities. Exergy indicates the quality of energy, and in any real process, it need not be conserved, but it is destroyed or lost.

The reference environment

Exergy is always evaluated with respect to a reference environment. The reference environment is in stable equilibrium, acts as an infinite system, and is a sink or source for heat and materials, and experience only internal reversible processes in which its intensive properties remain constant (Hepbasli, 2004; Esen et al., 2007; Dincer et al., 2004b). According to the weather and climate condition in Malaysia, during calculations, the temperature T_0 and pressure P_0 of the environment are often taken as standard-state values, such as 25 ℃ and 100 kPa respectively (Saidur et al., 2010a; 2007b).

Energy and exergy efficiencies of processes

The expression of energy (η) and exergy (ψ) efficiencies for the principle type of processes are considered in the present study based on the following definitions (Dincer et al., 2004b, c; Esen et al., 2007; Saidur et al., 2007b; Hasanuzzaman et al., 2010):

$$\eta = \frac{\text{Energy in product outputs}}{\text{Eenergy in inputs}} \quad (7)$$

$$\psi = \frac{\text{Exergy in product outputs}}{\text{Exergy in inputs}} \quad (8)$$

DATA COLLECTION

Pusat Tenaga Malaysia (PTM) had conducted a survey of about 50, along with 4 steel and iron industries in Malaysia. In this study, the data has been collected from PTM for an annealing furnace in January, 2010. Diesel is used as fuel in the furnace. Necessary data for the analysis of the annealing furnace is shown in Table 1.

ANALYTICAL APPROACHES

This section describes the method used to estimate the energy and exergy use, energy and exergy efficiencies, energy savings and cost benefits for an annealing furnace. For a general steady state, steady-flow process, the following equations are applied to find the work and heat interactions, the rate of exergy decrease, the rate of irreversibility, the energy and exergy efficiencies (Hepbasli and Akdemir, 2004; Dincer et al., 2004d; Utlu et al., 2006). The mass balance equation can be expressed in the rate form as:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (9)$$

The general energy balance can be expressed as:

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \quad (10)$$

Annealing furnace system

Heat balance analysis based on the first law of thermodynamics is the primary method to analyze energy use characteristics in the furnace. This method is used to analyze the situation of energy use and evaluate integrity of systems or equipments according to the conservation of energy principle, which may be expressed as follows:

The net change (increase or decrease) in the total energy of the system during a process is equal to the difference between the total energy entering and the total energy leaving the system during that process (Zaili et al., 2010; Tong et al., 1995). A furnace can be divided into two parts; combustor chamber and annealing chamber as shown in Figure 3.

Energy and exergy analysis for combustion chamber

Chemical reaction in combustion chamber

The composition of the reactants (fuel and air) of a combustible mixture and the composition of the products depend only on the conservation of mass of each chemical element in the reactants. If sufficient oxygen is available, a hydrocarbon fuel can be completely oxidized. The carbon in the fuel is then converted to carbon dioxide (CO_2) and the hydrogen to water (H_20) (Heywood, 1988). Considering the complete combustion of a general hydrocarbon fuel having average molecular composition C_aH_b with air, the overall complete combustion equation can be written as:

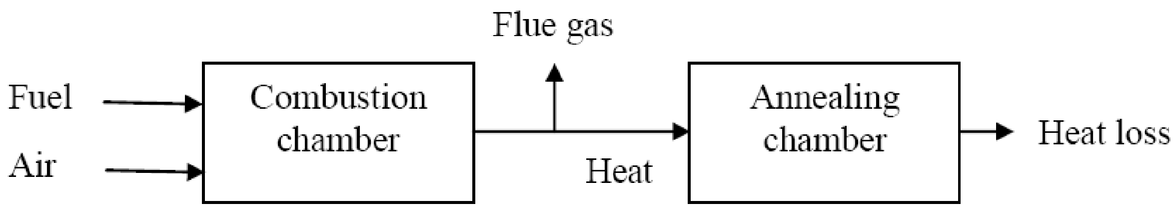

Figure 3. Schematic diagram of combustion and annealing chamber of a furnace.

Table 2. Enthalpy and entropy of the different parameter.

Substance	Enthalpy (kj/kg)	Entropy (kj/kg °C)
Air	298.2	1.6
Fuel	46,100.0	2.2
Hot product	3538.1	7.1
Flue gas	798.8	3.2

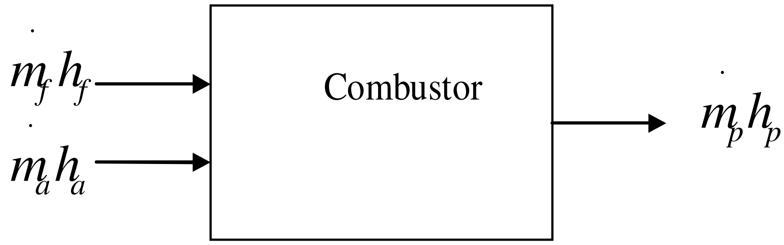

Figure 4. Schematic energy flow diagram of combustion chamber.

$$C_aH_b+(a+\frac{b}{4})(O_2+3.77N_2)=aCO_2+\frac{b}{2}H_2O+3.77(a+\frac{b}{4})N_2 \quad (11)$$

Diesel is used in the furnace as fuel. So, the following chemical reaction occurs in the combustion chamber:

$$C_{12}H_{23}+(O_2+3.77N_2)\rightarrow CO_2+H_2O+N_2 \quad (12)$$

In this study, complete combustion has been considered. Using stoichiometric mixture (air-fuel mixture), the chemical reaction can be written as follow:

$$2C_{12}H_{23}+35.5(O_2+3.77N_2)\Rightarrow 24CO_2+23H_2O+133.8N_2 \quad (13)$$

Thermodynamic properties (enthalpy and entropy) of different input and output parameters have been taken from the properties table of a thermodynamic book (Changel and Boles, 2006) and some of them are calculated, using the formula described earlier and as shown in Table 2.

Energy analysis for a combustor

Combustion chamber is the most important part of the furnace. Heat is produced by burning fuel in the combustor that is transferred to the annealing chamber. The combustor is usually well insulated to reduce the heat dissipation to the surrounding and thus the heat dissipation is considered almost zero. The involvement to do any kind of works, kinetic and potential energies of the fluid streams are usually negligible. That is why, only the input energy (air and fuel) and output energy (hot produced) are to be considered for analysis. According to the law of conservation of energy, the input energy is equal to the output energy that is shown in Figure 4.

Energy balance can be expressed as (Saidur et al., 2010a):

$$\dot{E}_{in}-\dot{E}_{out}=\frac{dE_{system}}{dt}=0 \implies steady \quad (14)$$

$$\dot{m}_f h_f+\dot{m}_a h_a-\dot{m}_p h_p=0 \quad (15)$$

$$\dot{m}_f h_f+\dot{m}_a h_a=\dot{m}_p h_p \quad (16)$$

Exergy analysis for a combustor

Exergy is a measure of the maximum capacity of a system to perform useful work as it proceeds to a specified final state in equilibrium with the surroundings. Exergy is generally not conserved as energy but is destroyed in the system. Exergy destruction is the measure of irreversibility that is the source of performance loss

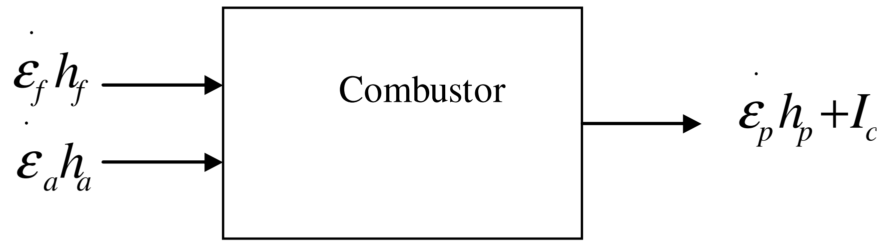

Figure 5. Schematic exergy flow diagram of combustor in a furnace.

(Aljundi, 2009a). The exergy change of a system during a process is equal to the difference between the net exergy transfer through the system boundary and the exergy destroyed within the system boundaries as a result of irreversibilities (Changel and Boles, 2006) as shown in Figure 5. The exergy balance for the combustion chamber can be written as follows (Aljundi, 2009a; Saidur et al., 2010a; Kalinci et al., 2010):

$$\dot{X}_{in} - \dot{X}_{out} - \dot{X}_{destroyed} = \frac{dX_{system}}{dt} = 0 ==> steady \quad (17)$$

$$(m_f \varepsilon_f + m_a \varepsilon_a) - m_p \varepsilon_p - I_C = 0 \quad (18)$$

$$\dot{I}_C = \dot{m}_f \varepsilon_f + \dot{m}_a \varepsilon_a - \dot{m}_p \varepsilon_p \quad (19)$$

Using Equation (8) and considering the above assumptions, the second law efficiency for combustor can be written as:

$$\psi_C = \frac{\dot{m}_p \varepsilon_p}{\dot{m}_f \varepsilon_f} \quad (20)$$

Energy and exergy analysis for an annealing chamber

The furnace can be modeled as a heat reservoir that supplies heat indefinitely at a constant temperature. The exergy of this heat energy is its useful work potential, that is, the maximum possible amount of work (Changel and Boles, 2006).

Energy analysis for an annealing chamber

Annealing chamber is considered as the furnace part where the product is heated inside the furnace. In the analysis, $\dot{Q}_{AP}$ is considered only the rate of heat input to the product processing in the annealing process that is shown in Figure 6.

According to Equation (7), the energy efficiency for the annealing chamber can be written as follows:

$$\eta_{AC} = \frac{\dot{Q}_{AP}}{\dot{m}_h (h_p - h_g)} \quad (21)$$

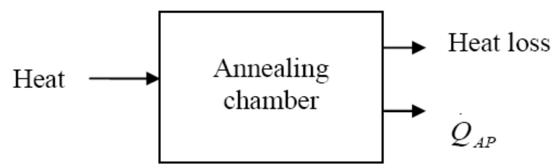

Figure 6. Schematic energy flow diagram of annealing chamber in a furnace.

Exergy analysis for an annealing chamber

Annealing furnace is considered as a heat reservoir from where the heat is input in the annealing chamber. Temperature in the annealing chamber is carefully controlled. In the analysis, temperature of the annealing chamber is considered as the average temperature of the annealing process. Considering the furnace as heat engine, energy efficiency (thermal efficiency) can be calculated as follow (Changel and Boles, 2006; Dincer et al., 2004b):

$$\eta_{AC} = 1 - \frac{T_{AC}}{T_C} \quad (22)$$

Energy exists in different forms (for example, heat or work), and energy is a measure of quantity. An energy source cannot be evaluated on its quantity alone. A measure of the quality of energy is its exergy, which is the work potential of energy in a given environment. For thermal energy, the Carnot efficiency represents the fraction of energy that can be converted to work (Dincer et al., 2004b). Exergy of the thermal energy can be calculated by using the following Equation (Dincer et al., 2004b; Çamdali and Tunç, 2003):

$$\text{Rate of exergy of heat transfer} = (1 - \frac{T_{AC}}{T_C}) \dot{Q}_{AP} \quad (23)$$

Rate of exergy destruction of the annealing chamber can be calculated by the following Equation:

$$\dot{I}_{AC} = \dot{m}_h (\varepsilon_p - \varepsilon_g) - (1 - \frac{T_{AC}}{T_C}) \dot{Q}_{AP} \quad (24)$$

Using Equation (8) and the above assumptions, exergy efficiency for annealing chamber can be written as:

$$\psi_{AC} = \frac{(1 - \frac{T_{AC}}{T_C})\dot{Q}_{AP}}{\dot{m}_h(\varepsilon_p - \varepsilon_g)} \quad (25)$$

Furnace overall efficiency

Overall energy efficiency of the furnace can be obtained by using the following formula:

$$\eta_F = \frac{\dot{Q}_{AP}}{\dot{m}_f\, h_f} \quad (26)$$

Overall exergy destruction of the furnace is obtained by adding the rate of exergy destruction of the combustion chamber and annealing chamber as follows:

$$\dot{I}_F = \dot{I}_C + \dot{I}_{AC} \quad (27)$$

Overall exergy efficiency of the furnace can be obtained by using the following formula:

$$\psi_F = \frac{(1 - \frac{T_{AC}}{T_C})\dot{Q}_{AP}}{\dot{m}_h\, \varepsilon_f} \quad (28)$$

Heat recovery from the flue gas

A significant amount of energy is lost through the flue gas of the furnace. Average temperature of the flue gas is about 390 °C. Recovering part of the heat from the flue gas can help to improve the efficiency of the furnace. Heat can be recovered from the flue gas by passing it through a heat exchanger that is installed after the furnace. Then, the recovered heat can be used to preheat combustion air and this will absolutely save the energy use. Heat recovery from flue gas can be expressed as (Hasanuzzaman et al., 2009):

Rate of heat recovered, $\dot{Q}_r = \dot{m}_g \times c_p \times \Delta T_d$ (29)

The annual fuel savings associated with the above heat recovery can be calculated as:

Fuel savings $= \frac{\dot{Q}_r}{H_{ff}}$ (30)

The annual fuel cost savings can be calculated as:

Annual fuel cost savings $= AFS \times C$ (31)

A simple payback period for different energy saving strategies can be calculated by using Equation 32 (Hasanuzzaman et al., 2011).

Simple payback period (years) = $\frac{\text{Incremental cost}}{\text{Annual cost savings}}$ (32)

RESULTS AND DISCUSSION

Energy input, exergy destruction and exergy efficiency for the combustor

In the furnace, only fuel is used as an energy supply. According to the thermodynamic analysis, air is also included in the energy balancing that is described in the analytical section. Considering complete combustion, input energy in the furnace system is about 556.3 kJ/s. In this study, the combustion chamber is considered as an adiabatic system. Since the furnace is an adiabatic combustor and the specific enthalpy of the fuel is equal to the higher heating value, the efficiency is always 100% (Saidur et al., 2010a). The temperature of the hot products is higher as compared to the annealing chamber in the annealing furnace. There is a rapid temperature reduction in this process; due to this reason, exergy is destroyed rapidly. Apart from the temperature variation, the irreversibilities in combustion reaction also cause exergy destruction (Aneta and Gheorghe, 2008). According to the exergy balance; rate of exergy destruction and exergy efficiency of combustor is calculated using Equations (19) and (20). The rate of exergy destruction and exergy efficiency of combustor are 215.1 kJ/s and 47.1% respectively.

Exergy destruction, energy and exergy efficiencies for the annealing chamber

Energy efficiency of the annealing chamber has been calculated by using Equation (21). Considering the one dimensional heat transfer from hot product to steel product, annealing chamber energy efficiency is 17.7%. In this study, the exergy analysis is based on heat transfer (Akpinar, 2006). Rate of exergy destruction and exergy efficiency of the annealing chamber have been calculated by using Equations (24) and (25). The rate of exergy destruction and exergy efficiency of annealing chamber are 283.8 kJ/s and 12.9% respectively.

Exergy destruction, energy and exergy efficiencies for the overall furnace

The overall furnace energy efficiency is calculated by using Equation (26) and was found to be 16.7%. The rate of exergy destruction and exergy efficiency of the furnace have been calculated using Equations (27) and (28). The rate of exergy destruction and exergy efficiency of the furnace are 498.9 kJ/s and 7.3% respectively. The result shows that exergy efficiency of the furnace is 7.3% where

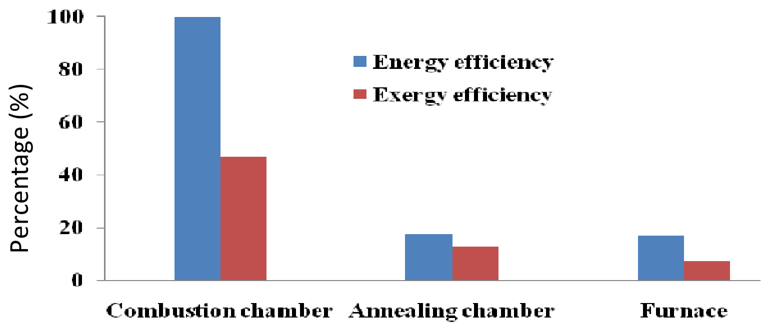

Figure 7. Energy and exergy efficiencies of annealing furnace.

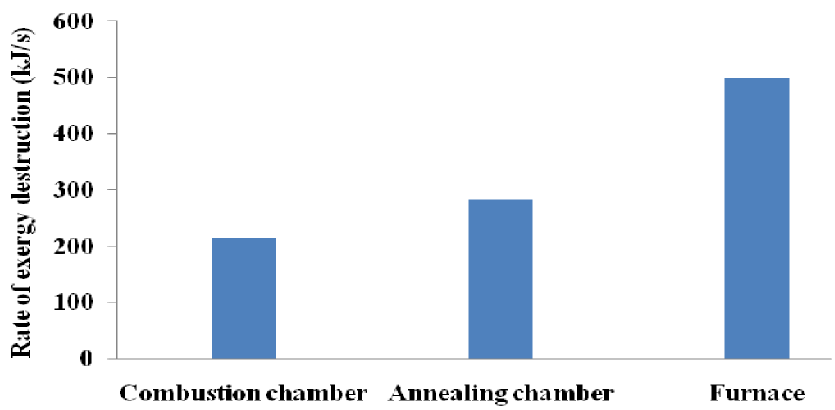

Figure 8. Rate of exergy destruction of the furnace.

the energy efficiency is 16.7%. The exergy efficiency is low due to the process irreversibility of the annealing furnace.

Heat recovery from flue gas and energy savings

A significant amount of energy is lost through the flue gas of the furnace. Average temperature of the flue gas is about 390°C. Since the minimum allowable stack gas temperature is 120°C, so the reduction in temperature for the flue gas can be achieved up to 270°C. Recovering heat from the flue gas can help to improve the efficiency of the furnace. Heat can be recovered from the flue gas by passing it through a heat exchanger that is installed after the furnace. The recovered heat can be used to preheat the combustion air and this will absolutely save energy. The rate of heat recovered from flue gas is about 113.8 MJ/h. Assuming the heat content in the fuel is about 46.1 MJ/kg, the fuel saving is 3.1 l/h. A furnace is operated about 3780 h/yr, so the fuel saving is 11,642.4 l/yr and fuel cost saving is 17,463.6 RM/yr. By taking the cost of heat recovery system of the furnace RM 2400 (Kinsey et al., 2010), payback period is less than 2 months. Hence, within 2 months, the cost of a heat recovery system can be recovered if the system is used to save energy of the furnace. If the payback periods are less than one-third of the system life, it is indicated that the implementation of the system is very cost-effective (Saidur et al., 2010b). Modern burners can withstand much higher combustion preheated air. So, it is possible to use heat recovery system to preheat the combustion air in the exit of the flue gas (EED, 2010). The input energy is the flue gas. Fuel consumption can be reduced about 25% by using the preheated air of high temperature about 1327°C (Hasegawa et al., 2000).

Overall furnace analysis and comparison

The results of this study are summarized in Figures 7 and 8. The rate of exergy destruction in the furnace is 514.6 kJ/s. The exergy destruction in the annealing chamber is high (about 57%) as compared to the combustor (about 43%) of the furnace. Temperature difference is the driving force of heat transfer. It is a typical irreversible phenomenon that heat is transferred due to limited temperature difference, thus there is exergy loss existing in this process. Exergy loss due to heat transfer is related to temperature difference. The greater the temperature difference, the greater the exergy loss. On the contrary, the smaller the temperature difference, the smaller the exergy loss (Zaili et al., 2010).

The overall energy and exergy efficiencies of the furnace are about 16.7 and 7.3% respectively. Oil fired reheating furnace efficiency is about 25% (direct method), 24% (indirect method) (EPAF, 2009). It is found that rate of exergy destruction affect both energy and exergy efficiencies. Energy and exergy efficiencies increase with decreasing rate of exergy destruction. It is also found that exergy efficiency increases with increasing energy efficiency. Since no actual process is truly reversible, some entropy is generated during the process. The more irreversible a process, the larger the entropy generated during that process (Changel and Boles, 2006). For real processes, the exergy input always exceeds the exergy output, due to irreversibilities. Both exergy destruction and exergy waste represent exergy losses. However, large exergy destruction may imply a large use of exergy input that may cause environmental damage (Wall, 2002).

Conclusions

In this study, the furnace energy utilization has been investigated and found that the major exergy loss (57%) occurs in the annealing chamber. The energy efficiency is higher compared to the exergy efficiency in the combustor, annealing chamber and overall furnace system. The overall furnace energy efficiency is 16.7% where the exergy efficiency is only 7.3%. By using the heat recovery system, about 113.8 MJ/h can be recovered with the payback period of less than 2 months. Recovered heat can be used to preheat the combustion air that can help to improve the overall efficiency of the furnace and hence can save fuel for about 8.1% (for example, 3.1 l/h out of 38 l/h).

Nomenclature: a, Number of carbon atom of fuel; *AFS*, Annual fuel savings, l/yr; b ,Number of hydrogen atom of fuel; c ,Fuel cost, 1.50 RM/l; C_p ,Specific heat capacity, kJ/kg °C; $\frac{d}{dt}$,Rate of change with time; $\dot{E}$,Rate of energy; H_{ff} , Higher heating value, kJ/kg; ***h*** ,Specific enthalpy, kJ/kg; $\dot{I}$, Rate of exergy destruction, kJ/s; i , Partial molar properties; N_i , Mole fraction of gas component *l*; $\dot{m}$,Mass flow rate, kg/s; $\dot{Q}$, Rate of heat transfer, kJ/s; s ,Specific entropy, kJ/kg; **T,** Temperature, °C; ΔT_d, Temperature drop of the flue gas, °C; $\dot{X}$,Exergy of the system, kJ/s; γ_{ff} , Exergy grade function.

Greek symbols: ε ,Specific exergy, kJ/kg; ε_{ff} ,Specific chemical exergy, kJ/kg; η ,Energy efficiency (%); ψ ,Exergy efficiency (%).

Subscripts: a , Air; *AC*, Annealing chamber; ***AP*** , Annealing product; C ,Combustion chamber; f , Fuel; F ,Furnace; g ,Flue gas; in , Inlet condition; o ,Reference state; out ,Outlet condition; p , Hot product; r , Recovery.

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