Energy, exergy and economic analysis of industrial boilers

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ABSTRACT

In this paper, the useful concept of energy and exergy utilization is analyzed, and applied to the boiler system. Energy and exergy flows in a boiler have been shown in this paper. The energy and exergy efficiencies have been determined as well. In a boiler, the energy and exergy efficiencies are found to be 72.46% and 24.89%, respectively. A boiler energy and exergy efficiencies are compared with others work as well. It has been found that the combustion chamber is the major contributor for exergy destruction followed by heat exchanger of a boiler system. Furthermore, several energy saving measures such as use of variable speed drive in boiler's fan energy savings and heat recovery from flue gas are applied in reducing a boiler energy use. It has been found that the payback period is about 1 yr for heat recovery from a boiler flue gas. The payback period for using VSD with 19 kW motor found to be economically viable for energy savings in a boiler fan.

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1. Introduction

Nearly 45% of global electricity generation is derived from coal while natural gas and nuclear energy makes up about 20% and 15%, respectively of the world's electricity generation (Energy information administration, 2007). Since these energy sources generally use boiler–steam turbine system to convert its chemical potential energy to electricity generation, one can only imagine the possible way of savings derivable from improving the efficiency of a steam boiler by just a small fraction. Most of the heating systems, although not all, employ boilers to produce hot water or steam.

All of the major industrial energy users devote significant proportions of their fossil fuel consumption to steam production: food processing (57%), pulp and paper (81%), chemicals (42%), petroleum refining (23%), and primary metals (10%). Since industrial systems are very diverse, but often have major steam systems in common, it makes a useful target for energy efficiency measures (Einstein et al., 2001).

Boiler efficiency therefore has a great influence on heating-related energy savings. It is therefore important to maximize the heat transfer to the water and minimize the heat losses in the boiler. Heat can be lost from boilers by a variety of methods, including hot flue gas losses, radiation losses and, in the case of steam boilers, blow-down losses (ERC, 2004) etc. To optimize the operation of a boiler plant, it is necessary to identify where energy wastage is likely to occur. A significant amount of energy is lost through flue gases as all the heat produced by the burning fuel cannot be transferred to water or steam in the boiler. As the temperature of the flue gas leaving a boiler typically ranges from 150 to 250 °C, about 10–30% of the heat energy is lost through it. A typical heat balance in a boiler is shown in Fig. 1. Since most of the heat losses from the boiler appear as heat in the flue gas, the recovery of this heat can result in substantial energy savings (Jayamaha, 2008, Beggs, 2002).This indicates that there is huge savings potentials of a boiler energy savings by minimizing its losses. Having been around for centuries, the technology involved in a boiler can be seen as having reached a plateau, with even marginal increase in efficiency painstakingly hard to achieve (Sonia and Rubin, 2007).

The First Law of Thermodynamics is conventionally used to analyze the energy utilization, but it is unable to account the quality aspect of energy. That is where exergy analysis becomes relevant. Exergy is the consequent of Second Law of Thermodynamics. It is a property that enables us to determine the useful work potential of a given amount of energy at some specified state. Exergy analysis has been widely used in design, simulation and performance evaluation of thermal and thermo-chemical systems. The energy use of a country has been assessed using exergy analysis to gain insight of its efficiency and potential for further improvement. Exergy investigations of the energy use were first introduced in USA by Reistad (1975) and have been carried out for various countries such as Canada (Rosen, 1992) Japan, Finland and Sweden (Wall, 1990), Italy (Wall et al., 1994), Turkey (Ozdogan and Arikol, 1995; Rosen and Dincer, 1997; Utlu and Hepbasli, 2003, 2005), UK (Hammond and Stepleton, 2001), Norway (Ertasvag and Mielnik, 2000; Ertasvag, 2005), China (Xi and Chen, 2005), Malaysia (Saidur et al., 2007a, b, c, Saidur

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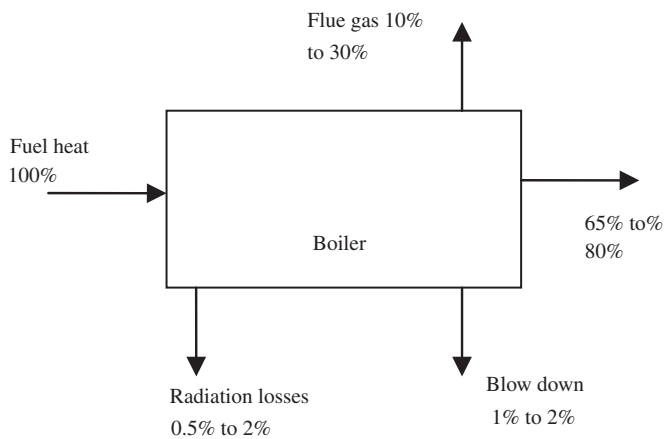E-mail address: saidur@um.edu.my (R. Saidur).

Fig. 1. Typical heat balance of a boiler (Jayamaha, 2008).

et al., 2006) and Saudi Arabia (Dincer et al., 2004a, b, c). Kanoglu et al. (2005, 2007), Som and Datta (2008), Szargut et al. (1988), Al-Ghandoor et al. (2009), Karakus et al. (2002), Kotas (1985), Rivero and Anaya (1997), and Hammond and Stepleton (2001) presented energy and exergy analysis for different industrial processes and systems for different countries.

Dincer et al. (2004a) discussed that exergy appears to be a key concept, since it is a linkage between the physical and engineering world and the surrounding environment, and expresses the true efficiency of engineering systems, which makes it a useful concept to find improvements.

As a complement to the present materials and energy balances, exergy calculations can provide increased and deeper insight into the process, as well as new unforeseen ideas for improvements. Consequently, it can be highlighted that the potential usefulness of exergy analysis in sectoral energy utilization is substantial and that the role of exergy in energy policy making activities is crucial (Dincer et al., 2004b).

An understanding of both energy and exergy efficiencies is essential for designing, analyzing, optimizing and improving energy systems through appropriate energy policies and strategies. If such policies and strategies are in place, numerous measures can be applied to improve the efficiency of industrial boilers (Kanoglu et al., 2007).

An exergy analysis is usually aimed to determine the maximum performance of the system and/or identify the sites of exergy destruction. Identifying the main sites of exergy destruction, causes of destruction, true magnitude of destructions, shows the direction for potential improvements for the system and components, (Kanoglu et al., 2005, 2007). Dincer (2002a–b) reported the relation between energy and exergy, exergy and the environment, energy and sustainable development, and energy policy making in details. So from the above discussions and literatures it is obvious that analysis of exergy is crucial for energy planning, resource optimization and global environmental, regional, and national pollution reduction.

Exergy analysis that may be regarded as accounting of the use of energy and material resources provides information as to how effective and how balanced a process is in the matter of conserving natural resources (Szargut et al., 1988). This type of information makes it possible to identify areas in which technical and other improvements could be undertaken and indicates the priorities that could be assigned to conservation procedures. Exergy conscious utilization of energy sources would help advance technological development towards resource-saving and efficient technology can be achieved by improving design of processes with high exergetic efficiency. Application of the exergy

analysis in design and development of sustainable processes also provides information for long-term planning of resource management (Kotas, 1985).

Jamil (1994) studied thermodynamics performance of Ghazlan power plant in Saudi Arabia where mixture of methane, ethane and propane were used as fuels. Author found that exergy efficiency in the boiler furnace was about 18.88%. Author also found the total losses are high in the boiler especially in the heat exchanger (43.4%) compared to other devices. Author also studied Qurayyah power plant whee exergy efficiency in the furnace was about 16.88% and in the heat exchanger 25.19%.

Gonzalez (1998) studied the improvement of boiler performance by using economizer model. Author used hot gases recovery system to improve the performance of the boiler. Author reported that up to 57% of cost can be saved with the heat recovery system.

In this study energy, exergy efficiency, energy losses, and exergy detruction for a boiler is identified and ways to reduce boiler energy consumption using variable speed drive and nanofluids to enhance heat transfer applied and energy and economic benefit have been analyzed. It may be noted that a boiler energy use can be reduced by many other ways for example by controlling excess air, enhancing heat transfer rate, improving combustion efficiency, use of more environmental friendly fuel, recovering waste heat, recovering condensate, optimizing blow-down process, preventing leakage and providing proper insulation. Economic benefits associated with energy savings has been analyzed and presented as well.

It is important to note that exergy destructions are due to irreversibilities in the turbine, pump and condenser. The primary way of keeping the exergy destruction in a combustion process within a reasonable limit is to reduce the irreversibility in heat conduction through proper control of physical processes and chemical reactions resulting in a high value of flame temperature but lower values of temperature gradients within the system. The optimum operating condition in this context can be determined from the parametric studies on combustion irreversibilities with operating parameters in different types of flames. The most efficient performance is achieved when the exergy loss in the process is the minimum. These can be done by optimizing heat exchangers, fins, thermal insulation, combustion process (Som and Datta, 2008).

In this study exergy analysis on a boiler is done according to the method used by Rosen (1999) and Aljundi (2009b). As a boiler is used in many industrial applications and use significant amount of energy, its efficiency improvement and reduced losses/exergy destruction will play a significant role in energy savings and mitigation of environmental pollution. It may be stated that this study will be useful to policy makers, engineers, industrial energy users and scientist in industrial boiler energy use.

2. General mathematical tools for analysis

This section discussed several basic quantities and mathematical relations for the energy and exergy analysis.

2.1. Chemical exergy

At near ambient conditions, Dincer et al. (2004a) described that specific exergy of hydrocarbon fuels reduces to chemical exergy and can be written as

$$\varepsilon_{ff} = \gamma_{ff} H_{ff} \qquad (1)$$

Where γ_{ff} denotes the fuel exergy grade function, defined as the ratio of fuel chemical exergy and heating value. Table 1 shows

Table 1
Properties of selected fuels (Saidur et al., 2007b).

Fuel	Heating value, H_{ff} (kJ/kg)	Chemical exergy, ε_{ff} (kJ/kg)	Exergy grade function, γ_{ff}
Gasoline	47849	47394	0.99
Fuel oil	47405	47101	0.99
Kerosine	46117	45897	0.99

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 higher heating value, H_{ff} (Dincer et al., 2004a).

2.2. 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 (i.e. temperature T_0, pressure P_0 and chemical properties μ_{j00} for each of the j component) remains constant. Based on weather and climate condition in Malaysia, with minor modifications of the Gaggioli and Petit's model (1977) which is recommended by Dincer (2004b), this analysis used $T_0=25\,°C$ as the surrounding temperature, $P_0=100\,kPa$ as the surrounding pressure and the chemical composition is taken to be air saturated with water vapor, and the following condensed phases are used at 25 °C and 100 kPa: water (H_2O), gypsum ($CaSO_4 \cdot 2H_2O$) and limestone ($CaCO_3$) (Dincer, 2004a).

2.3. Energy and exergy efficiencies for principle types of processes

The expression of energy (η) and exergy (ψ) efficiencies for the principle types of processes considered in the present study are based on the following definitions:

$$\eta = \frac{\text{energy in products}}{\text{total energy input}} \qquad (2)$$

$$\psi = \frac{\text{exergy in products}}{\text{total exergy input}} \qquad (3)$$

Exergy efficiencies for the fuels in Table 1 can often be written as a function of the corresponding energy efficiencies by assuming the energy grade function γ_{ff} to be 'unity', energy use equals to exergy use (Dincer et al., 2004a).

3. Analytical approaches

This section describes about the method used to estimate the energy and exergy use, energy and exergy efficiencies for a boiler. The energy saving options to reduce boiler flue gas temperature and use of VSD in reducing a boiler's fan energy use are discussed along with their cost-benefit analysis.

3.1. Energy and exergy analysis for a boiler

A boiler can be divided into heat exchanger and combustor as shown in Fig. 2. The energy and exergy analysis of these two parts have been discussed below.

Data for the boiler has been taken from Department of Occupational Safety and Health (DOSH)

For the complete combustion in the chamber, the air-fuel ratio has been used as 15:1. The necessary data has been shown in
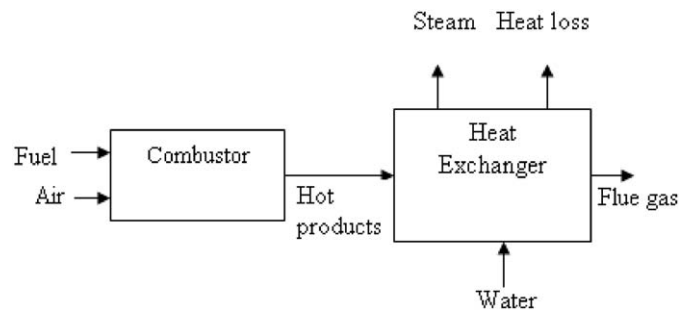

Fig. 2. Schematic diagram of combustor and heat exchanger in a boiler (Changel and Boles, 2006).

Table 2. However, the enthalpy and entropy properties are taken from REFPROP 7. Mass flow rates of fuel and air have been calculated from the data of hot products using air-fuel ratio of 15:1.

For the complete combustion, stoichiometric air has to be supplied. Methane is considered as a fuel. The following chemical reaction is occurred in the combustion chamber:

$$CH_4 + 2(O_2 + 3.76N_2) \Rightarrow CO_2 + 2H_2O + 7.52N_2 \qquad (4)$$
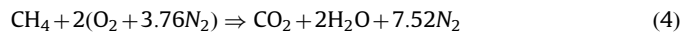
For the complete combustion, the air-fuel ratio has been considered as 15:1. Entropy of the flue gas and hot products are obtained using Table A-18 to Table A-20 and Table A-27 from Ref. Changel and Boles (2006).

3.1.1. First law analysis on combustor

The combustor in a boiler is usually well insulated that causes heat dissipation to the surrounding almost zero. It also as no involvement to do any kind of work ($w=0$). Also, the kinetic and potential energies of the fluid streams are usually negligible. Then only total energies of the incoming streams and the outgoing mixture remained for analysis. The conservation of energy principle requires that these two equal each others. Besides, the sum of the incoming mass flow rates will be equal to the mass flow rates of the outgoing mixture. The energy balance for the combustor is shown in Fig. 3:

Taking mass flow rate for fuel as $\dot{m}_f$, mass flow rate for air as $\dot{m}_a$, and mass flow rate for products as $\dot{m}_p$, energy balance can be expressed as:

$$\dot{E}_{in} - \dot{E}_{out} = \frac{dE_{system}}{dt} = 0 == > steady \qquad (5)$$

$$\dot{E}_{in} = \dot{E}_{out} \qquad (6)$$

$$\dot{m}_f h_f + \dot{m}_a h_a - \dot{m}_p h_p = 0 \qquad (7)$$

$$\dot{m}_f h_f + \dot{m}_a h_a = \dot{m}_p h_p \qquad (8)$$

where, h_f=specific enthalpy of fuel, kJ/kg, h_a=specific enthalpy of air, kJ/kg, h_p=specific enthalpy of hot products of combustion, kJ/kg

With the above assumptions, the appropriate first law efficiency for combustor can be written as:

$$\eta_C = \frac{\dot{m}_p h_p}{\dot{m}_f h_f} \qquad (9)$$

The specific enthalpy of the fuel, h_f, is evaluated such that it is equal to the higher heating value ($H_L=55,530\,kJ/kg$). For an adiabatic combustor, the efficiency in Eq.(9) always yield $\eta_C=100\%$.

Table 2
Data for mass flow rate, temperature, enthalpy and entropy on the basis of DOSH (DOSH, 2009, REFPROP 7).

Substances	Mass flow rate kg/s	Temperature °C	Enthalpy kJ/kg	Entropy kJ/kg°C
Air, m_a	4.125	126.85	400.98	1.9919
Fuel, m_f	0.275	1243.99	50,050.00	2.0
Hot Products, m_p	4.40	250	3504.00	7.0716
Water, m_w	4.22	100	419.15	1.307
Steam, m_s	4.22	185.334	2782.73	6.546
Flue gas, m_g	4.40	212.57	361.44	1.9
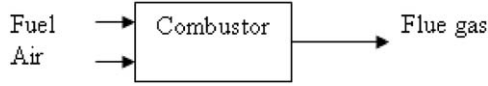
Fig. 3. Schematic diagram of combustor in a boiler (Changel and Boles, 2006).

3.1.2. Second law analysis on combustor

The maximum power output or reversible power is determined from the exergy balance applied to the boiler considering boundary with an environment temperature of T_0 (T_0=25 °C) and by assuming the rate of change in exergy in the boiler's system is zero. The exergy balance formulations have been established using methodology developed by (Aljundi, 2009a; Dincer and Rosen, 2007).

$$\dot{X}_{in} - \dot{X}_{out} - \dot{X}_{destroyed} = \frac{dX_{system}}{dt} = 0 == > steady \tag{10}$$

$$(m_f \varepsilon_f + m_a \varepsilon_a) - m_p \varepsilon_p - I_C = 0 \tag{11}$$

$$\dot{I}_C = \dot{m}_f \varepsilon_f + \dot{m}_a \varepsilon_a - \dot{m}_p \varepsilon_p \tag{12}$$

where, I_C=Exergy destruction, $\varepsilon_a, \varepsilon_f$ and ε_p are exergy of air, fuel and products respectively.

Appropriate second law efficiency for the combustor is analogous to the combustor's energy efficiency and can be written as

$$\psi_C = \frac{\dot{m}_p \varepsilon_p}{\dot{m}_f \varepsilon_f} \tag{13}$$

3.1.3. First law analysis on heat exchanger

Heat exchanger is a device where two moving fluid streams exchange heat without mixing. Heat is transferred from the hot fluid to the cold one through the wall separating them. A heat exchanger typically involves no work interactions (w=0) and negligible kinetic and potential energy changes for each fluid streams. Basically, the outer shell of the heat exchanger is usually well insulated to prevent any heat loss to the surrounding medium. However, there is a little amount of heat that will be dissipated. The energy balance for heat exchanger is shown in Fig. 4.
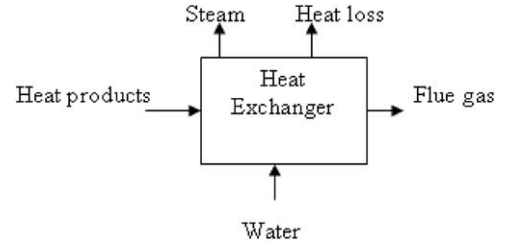
Taking mass flow rate for heat products as $\dot{m}_p$, mass flow rate for flue gas as $\dot{m}_g$, mass flow rate for water as $m_{\cdot l}$ and mass flow rate for steam as $\dot{m}_s$ and since, there is no mixing in heat exchanger, it can be assumed that $\dot{m}_p = \dot{m}_g = \dot{m}_H$ and $\dot{m}_l = \dot{m}_s = \dot{m}_C$.

With these assumptions energy balance can be expressed as:

$$\dot{E}_{in} - \dot{E}_{out} + \frac{dE_{system}}{dt} = 0 \tag{14}$$

$$\Rightarrow (\dot{m}_p h_p + \dot{m}_l h_l) - (\dot{m}_g h_g + \dot{m}_s h_s) = \dot{Q}$$

$$\Rightarrow \dot{m}_H(h_p - h_g) + \dot{m}_C(h_l - h_s) = \dot{Q}$$

Fig. 4. Schematic diagram of flow through a heat exchanger (Changel and Boles, 2006).

Thus,

$$\Rightarrow \dot{m}_H(h_p - h_g) + \dot{m}_C(h_s - h_l) = \dot{Q} \tag{15}$$

Appropriate first law efficiency for the heat exchanger can be written as follows:

$$(\dot{m}_p \varepsilon_p + \dot{m}_l \varepsilon_l) - (\dot{m}_g \varepsilon_g + \dot{m}_s \varepsilon_s) - \dot{I}_H = 0$$

$$\dot{m}_H(\varepsilon_p - \varepsilon_g) + \dot{m}_C(\varepsilon_l - \varepsilon_s) = \dot{I}_H$$

$$\eta_H = \frac{\dot{m}_c(h_s - h_l)}{\dot{m}_h(h_p - h_g)} \tag{16}$$

The energy efficiency of the overall boiler can be obtained by using the following formula:

$$\eta_B = \frac{\dot{m}_c(h_s - h_l)}{\dot{m}_f h_f} \tag{17}$$

3.1.4. Second law analysis of heat exchanger

By assuming the rate of change in exergy in the boiler's system is zero and the environment temperature at T_0 T_0=25 °C), the exergy balance can be expressed as (Aljundi, 2009a):

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

$$\dot{I}_H = \dot{m}_H(\varepsilon_p - \varepsilon_g) + \dot{m}_C(\varepsilon_l - \varepsilon_s) \tag{18}$$

Hence, the overall exergy balance for the boiler is obtained by adding the exergy balance of the combustor and heat exchanger:

$$\dot{I}_B = \dot{I}_C + \dot{I}_H \tag{19}$$

Appropriate second law efficiency for heat exchanger is analogous to the heat exchanger's energy efficiency and can be written as:

$$\psi_H = \frac{\dot{m}_c(\varepsilon_s - \varepsilon_l)}{\dot{m}_h(\varepsilon_p - \varepsilon_g)} \tag{20}$$

The exergy efficiency of the overall boiler can be obtained by using the following formula:

$$\psi_B = \frac{\dot{m}_c(\varepsilon_s - \varepsilon_l)}{\dot{m}_f \varepsilon_f} \tag{21}$$

Physical exergy analysis cannot be applied rationally to the overall boiler or the combustor due to the chemical compositions of some streams within the boiler's system is changing.

3.2. Energy and cost saving measures for a boiler

There are different methods that can be used to reduce boilers energy uses. However in this paper, boiler energy savings using variable speed drive in reducing speed of boiler fan and energy savings by heat recovery from flue gases in a boiler have been considered.

3.2.1. Optimizing operation of auxiliary equipment

Auxiliary equipment such as feed water pumps, boiler draft fans, hot water circulating pumps, and condensate pumps also consume an appreciable amount of energy. The energy and cost savings can be achieved by ensuring that they are operated only when required and at the capacity required to maintain system requirements. Fan operating time can be adjusted with loading conditions of the boiler as shown in Table 3. A boiler system can also be improved to reduce the energy use by installing variable speed drive (VSD) at the pumps or fans as shown as in Fig. 5.

The VSD also can be installed in a boiler fan. Boiler fans are used to create the draft necessary for combustion and carry the flue gases through the boiler. It normally operates at constant speed and dampers are used to control the air flow to match the boiler load conditions. However, when the boiler operates at part load, a damper throttles the air flow by inducing a resistance across the path of the air flow. Hence, by using of VSD, the reduction in fan energy use can be achieved by matching the speed requirements.

There are many ways of estimating the energy savings associated with the use of VSDs for industrial boilers for a range of applications. This paper uses the method found in Anon (2008).

Annual energy savings for boilers with VSD can be expressed as:

$$AES_{boiler\_VSD} = (AEC_{boiler\_without\_VSD} - AEC_{boiler\_with\_VSD}) \quad (22)$$

Table 3
Boiler operating data.

Boiler loading (%)	Operating hours in a year	Fan motor power (kW)
100	720	22
80	1440	21
60	3240	19
40	2520	16

Energy use in fans and pumps varies according to the speed raised to the third power, so small changes in speed can result in very large changes in energy use. A boiler's pumps and fan motors energy savings using a VSD can be estimated as:

$$AES_{VSD} = N \times P \times UH \times S_{SR} \quad (23)$$

AES_{VSD}-Energy savings with the application of VSD, S_{SR}-Percentage energy savings associated certain percentage of speed reduction (Taken from Table 4).

Table 4 shows the potential energy savings associated with the speed reduction using VSDs for pumps and fan motors. These data were then used to estimate pumps and fan motors energy savings using VSDs.

3.2.2. Heat recovery from flue gas

A significant amount of heat energy is lost through flue gases as all the heat produced by burning fuel cannot be transferred to water or steam in the boiler. As the temperature of the flue gas leaving a boiler is in the range of 150–250 °C, about 10–30 percent of the heat energy is lost through it. Therefore, recovering part of the heat from the flue gas can help to improve the efficiency of the boiler. Heat can be recovered from the flue gas by passing it through a heat exchanger that is installed after the boiler as shown in Fig. 6.

The recovered heat can be used to pre-heat boiler feed water, combustion air and this will absolutely save the energy use. The flue gas is usually at high temperature to ensure that it is enough to pre-heat the fluid. Heat recovery from flue gas can be expressed as:

Heat recovered,

$$Q_r = m_{fg} \times c_p \times \Delta T_{fg} \quad (24)$$

Table 4
Potential saving for variable speed.

Average speed reduction (%)	Potential energy savings (%)
10	22
20	44
20	61
40	73
50	83
60	89

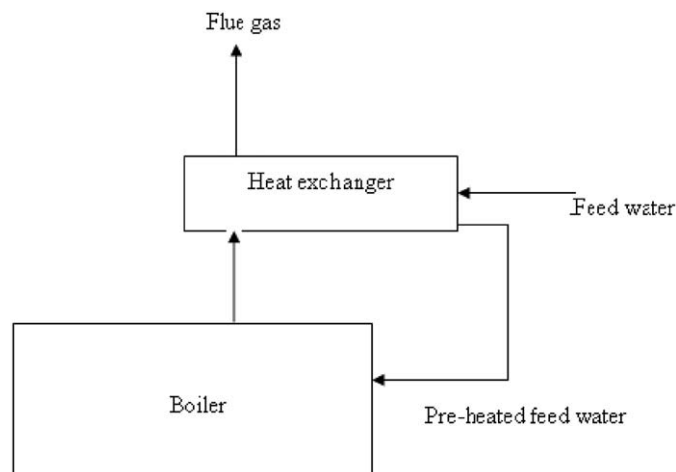**Fig. 5.** Schematic diagram of feed water pump with application of VSD (Jayamaha, 2008).

Fig. 6. Arrangement of typical heat exchanger with heat recovery system (Jayamaha, 2008).

Where, m_{fg} mass flow rate flue gases for heat recovery, C_p specific heat of flue gas and ΔT_p temperature drop of the flue gases.

Moreover, a boiler flue gas temperature can be reduced by using nanofluids. Saidur and Lai (2009) carried out an analysis of a boiler flue gas temperature reduction procedure using nanofluids. Details can be found in the reference.

3.2.3. Mathematical formulation for cost savings and payback periods

Cost savings associated with energy savings can be expressed as:

$$\text{Cost saved} = \text{Annual energy saved (AES)} \times \text{unit price of energy} \tag{25}$$

A simple payback period for different energy savings strategies can be estimated using Eq. (26) (Saidur et al., 2009).

$$\text{Payback Period} = \frac{\text{Incremental Cost}}{\text{Annual cost savings}} \tag{26}$$

4. Results and discussions

4.1. Analysis on boiler

4.1.1. Energy use of combustor

Considering the assumptions as explained in Section 3 and taking data from Table 4, the energy input can be calculated as:

$$E_{in} = \dot{m}_f h_f + \dot{m}_a h_a$$

$$= 0.275\,\text{kg/s}(50,050\,\text{kJ/kg}) + 4.125\,\text{kg/s}(400.98\,\text{kJ/kg})$$
$$= 15,417.8\,\text{kJ/s}$$

Since the boiler has an adiabatic combustor and the specific enthalpy of the fuel, h_f, is evaluated such that it is equal to the higher heating value, the efficiency is always 100%.

Therefore, the energy input in the boiler system is 15.4 MJ/s with the efficiency of 100%. This means that all the energy input is being sent to the heat exchanger and there is no heat loss to the environment.

4.1.2. Exergy destruction in the combustor

The exergy destruction of the combustor is estimated by using the Eq. (12). It is assumed that the combustor operates in steady-flow process since there is no change in process with time at any point, thus change of mass and energy of the control volume of combustor is equal to zero ($\Delta m_{cv} = 0, \Delta E_{cv} = 0$). It is also assumed that there is no work interaction involved and the kinetic and potential energies are negligible. Using Eq. (12) and data from Table 2, exergy destruction has been calculated as follows:

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

$$= \dot{m}_f(h_f - T_0 s_f) + \dot{m}_a(h_a - T_0 s_a) - \dot{m}_p(h_p - T_0 s_p)$$
$$= 0.275\,\text{kg/s}[50,050\,\text{kJ/kg} - 298\,\text{K}(2\,\text{kJ/kgK})]$$
$$\quad + 4.125\,\text{kg/s}[400.98\,\text{kJ/kg} - 298\,\text{K}(1.9919\,\text{kJ/kgK})]$$
$$\quad - 4.40\,\text{kg/s}[3504\,\text{kJ/kg} - 298\,\text{K}(7.0716\,\text{kJ/kgK})] = 6,660\,\text{kJ/s}$$

The appropriate second law efficiency for combustor is calculated using Eq. (13) and data from Table 2 as follows:

$$\psi_C = \frac{\dot{m}_p \varepsilon_p}{\dot{m}_f \varepsilon_f} = \frac{\dot{m}_p(h_p - T_0 s_p)}{\dot{m}_f(h_f - T_0 s_f)}$$

$$= \frac{4.4\,\text{kg/s}[3504\,\text{kJ/kg} - 298\,\text{K}(7.0716\,\text{kJ/kgK})]}{0.275\,\text{kg/s}[50,050\,\text{kJ/kg} - 298\,\text{K}(2.0\,\text{kJ/kgK})]} = 45.18\%$$

Thus, exergy destruction of the combustor is equal to 6660 MJ/s with the efficiency of 45.18%. It may be stated that exergy destruction is high since the combustor is not fully adiabatic and combustion may not be complete.

4.1.3. Energy use in the heat exchanger

Considering same assumptions in Section 4.1.2 and by taking the entire heat exchanger as the control volume, the heat loss from the system is calculated by using Eq. (14) and data from Table 2.

$$\dot{Q} = \dot{m}_H(h_p - h_g) - \dot{m}_C^{\cdot}(h_s - h_l)$$
$$= 4.40\,\text{kg/s}(3504\,\text{kJ/kg} - 361.44\,\text{kJ/kg})$$
$$\quad - 4.22\,\text{kg/s}(2782.73\,\text{kJ/kg} - 419.15\,\text{kJ/kg}) = 3853\,\text{kJ/s}$$

The appropriate first law efficiency for heat exchanger is calculated using Eq.(16) and data from Table 2 as follows:

$$\eta_H = \frac{\dot{m}_c(h_s - h_l)}{\dot{m}_h(h_p - h_g)}$$

$$= \frac{4.22\,\text{kg/s}(2782.73\,\text{kJ/kg} - 419.15\,\text{kJ/kg})}{4.40\,\text{kg/s}(3504\,\text{kJ/kg} - 361.44\,\text{kJ/kg})}$$
$$= 0.7213 = 72.13\%$$

Therefore, there is about 3.85 MJ/s of energy is dissipated through the heat exchanger and about 72.13 percent of energy is used to heat up water.

The overall boiler energy efficiency is calculated using Eq. (17) and data from Table 2 as follows:

$$\eta_B = \frac{\dot{m}_c(h_s - h_l)}{\dot{m}_f h_f}$$

$$= \frac{4.22\,\text{kg/s}(2782.73\,\text{kJ/kg} - 419.15\,\text{kJ/kg})}{0.275\,\text{kg/s}(50,050\,\text{kJ/kg})}$$
$$= 0.7246 = 72.46\%$$

Fig. 7 shows the exergy flow in the combustor of the boiler.

4.1.4. Exergy destruction in the heat exchanger

The exergy destruction of the heat exchanger is estimated using the methodology described in the Section 3.1.4.

Using same assumptions as shown in Section 4.1.2, the exergy destruction is calculated by using Eq. (18) and data from Table 2.

$$\dot{I}_H = \dot{m}_H(\varepsilon_p - \varepsilon_g) + \dot{m}_C(\varepsilon_l - \varepsilon_s)$$

$$= \dot{m}_H[(h_p - T_0 s_p) - (h_g - T_0 s_g)] + \dot{m}_C[(h_l - T_0 s_l) - (h_s - T_0 s_s)]$$
$$= 4.40\,\text{kg/s}[(3504\,\text{kJ/kg} - 298\,\text{K}(7.0716\,\text{kJ/kg.K}))$$
$$\quad - (361.44\,\text{kJ/kg} - 298\,\text{K}(1.9\,\text{kJ/kg.K}))]$$
$$\quad + 4.22\,\text{kg/s}[(419.15\,\text{kJ/kg} - 298\,\text{K}(1.3071\,\text{kJ/kgK})) = 3660\,\text{kJ/s}$$
$$\quad - (2782.73\,\text{kJ/kg} - 298\,\text{K}(6.5460\,\text{kJ/kgK}))]$$
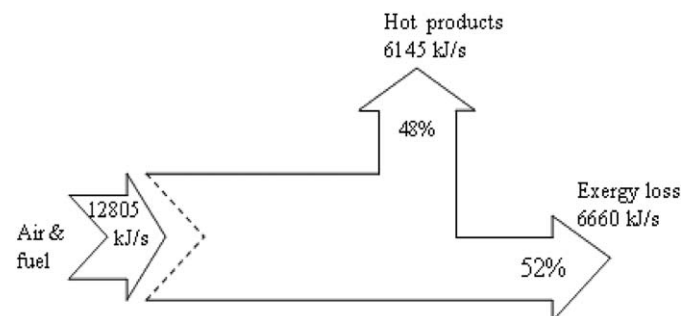

Fig. 7. Grassman diagram for exergy flow in the combustor.

The appropriate second law efficiency for heat exchanger is calculated using Eq. (20) and data from Table 2 as follows:

$$\psi_H = \frac{\dot{m}_c(\varepsilon_s - \varepsilon_l)}{\dot{m}_h(\varepsilon_p - \varepsilon_g)}$$

$$= \frac{\dot{m}_C[(h_S - T_0 s_S) - (h_L - T_0 s_L)]}{\dot{m}_H[(h_p - T_0 s_p) - (h_g - T_0 s_g)]}$$

$$= 0.4854 \approx 48.054\%$$

Thus, the overall exergy balance for the boiler is obtained by adding the exergy balance of the combustor and heat exchanger using Eq. (19).

$$\dot{I}_B = \dot{I}_C + \dot{I}_H$$

$$= 6,660\,kJ/s + 3660\,kJ/s$$

$$= 10,320\,MJ/s$$

The overall boiler exergy efficiency is calculated using Eq. (21) and data from Table 2 and can be expressed as:

$$\psi_B = \frac{\dot{m}_c(\varepsilon_s - \varepsilon_l)}{\dot{m}_f \varepsilon_f}$$

$$= \frac{\dot{m}_C[(h_S - T_0 s_S) - (h_L - T_0 s_L)]}{\dot{m}_f(h_f - T_0 s_f)}$$

$$= \frac{\begin{array}{c}4.22\,kg/s[(2782.73\,kJ/kg - 298\,K(6.5460\,kJ/kg\,K) \\ -(419.15\,kJ/kg - 298\,K(1.3071\,kJ/kg\,K))]\end{array}}{0.275\,kg/s[50,050\,kJ/kg - 298\,K(2.0\,kJ/kg\,K)]}$$

$$= 0.2489 \approx 24.89\%$$

Results obtained as above are summarized in Tables 5 and 6. Fig. 8 shows the exergy flow in the heat exchanger. Fig. 9 shows energy flow diagram of a boiler.

The overall energy use (i.e. 19,270.8 kJ/s) of the boiler is quite high. Normally, the low amount of energy is required in order to ensure the water to be heated and to produce a good quality of steam or hot water. The exergy destruction (i.e.10,320 kJ/s) in the boiler system is also high. The combustor part contributes the biggest amount of the exergy destruction. Since temperature of the air-fuel during entrance in the combustor and that in the chamber is high and this differences in the temperatures causes more exergy destruction in the combustor. Since the process in the heat exchanger involves different temperature gradient between the tubes in the exchanger, there is a tendency to produce a waste energy which is dissipated through the heat exchanger.

Apart from that, the energy and exergy efficiencies are shown in Table 6 and indicate that the overall energy and exergy efficiencies for a boiler are about 72.46% and 24.89%, respectively. The efficiency is not just based on the specific heat input to the steam only but also based on the lower heating value of the fuel to incorporate the losses occurring in the boiler system due to

Table 5
Energy and exergy analysis for combustor, heat exchanger and boiler.

	Energy consumption, kJ/s	Exergy destruction, kJ/s
Combustor	15,417.8	6660
Heat Exchanger	3853.00	3660
Boiler	19,270.8	10,320

Table 6
Energy and exergy efficiencies of combustor, heat exchanger and boiler.

	Energy efficiency, η (%)	Exergy efficiency, ψ (%)
Combustor	100	45.18
Heat exchanger	72.13	48.054
Boiler	72.46	24.89
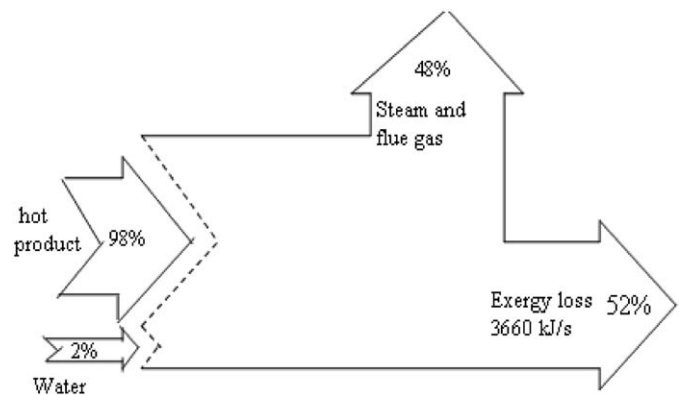
Fig. 8. Grassman diagram for flow of exergy in the heat exchanger.

energy lost with hot gases and incomplete combustion. The calculation of energy efficiency can often be misleading as it does not provide a measure of ideality. In addition, losses of energy can be large while it is thermodynamically insignificant due to low quality. However, exergy-based efficiency and losses provides measures of approach to ideality or deviation from ideality. The calculated exergy in a boiler system is quite low. This indicates that there are opportunities to improve the performance of a heat exchanger. However, it has to be noted that part of this irreversibility cannot be avoided due to physical, technological and economic constraints.

4.2. Comparative study of energy and exergy efficiencies of a boiler

It may be mentioned that so far only few studies have been done on exergy and energy analysis of boiler in a power plant. So, it is difficult to compare these data with other relevant works. It is observed that in most cases, major portion of exergy is lost in the combustor of a boiler. So, it should be taken into considerations for minimizing the losses in the combustion chamber. It may be due to incomplete combustion or improper insulation. Table 7 shows the comparison of energy and exergy efficiencies and losses in boilers with other works available in the literature.

4.3. Energy and cost saving

The estimation of energy and cost savings for a boiler has been carried out using the methodology described in Section 3.2 and discussed in following sections

4.3.1. Optimizing operation of auxiliary equipment
Energy savings associated with the use of VSD in fan motor speed reduction is estimated using Eq. (23) and data from Tables 3 and 4 are taken and for different percentage of speed reduction energy savings have been presented in Table 8.

Using data from Table 8 and Eqs. (25) and (26), payback periods for using VSD in a boiler's fan motor energy savings are shown in Table 9 considering energy price as RM 0.235/kWh.

4.3.2. Heat recovery from flue gas
In this analysis the boiler has a capacity of about 3000 kg/h with fuel flow rate 160 L/h and flue gas temperature of 204.4 °C. Since the minimum allowable stack temperature of natural gas is 120 °C, the reduction in temperature for the flue gas that can be achieved about 84.4 °C. Taking the density of natural gas as 800 kg/m³, the amount of fuel used is 128 kg/h and air-fuel ratio is about 15:1, the amount of combustion air is approximately 15 times the weight of fuel such that $15 \times 128 = 1920$ kg/h.
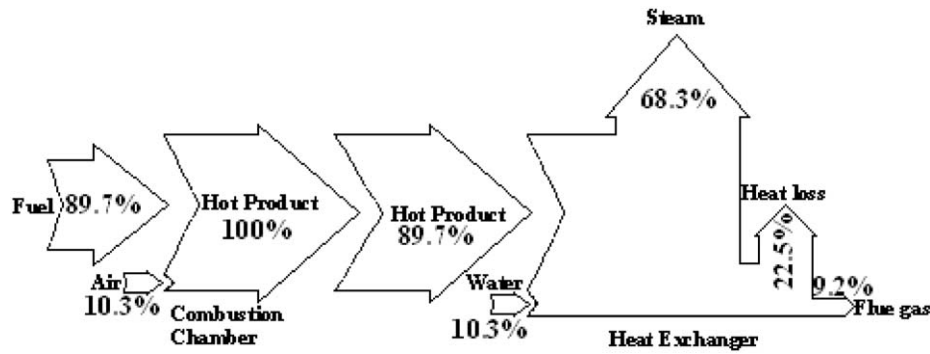
Fig. 9. Sankey diagram for energy flow through the combustor and heat ecchamber in a boiler.

Table 7
Data for energy and exergy efficiency obtained in different study for boiler.

Components	Energy efficiency%	Exergy efficiency%	Exergy loss%	Reference
Boiler	80.8	25	75	Balkrishna (2009)
Combustor	–	–	28.46	
Heat Exchanger	–	–	46.72	
Boiler	93.76	–	76.75	Aljundi (2009b)
Industry	62	40		Dincer et al. (2004a)
Industry	63.45–70.11	29.72–33.23		Utlu and Hepbasli (2007)
Industry	83	16		Oladiran and Meyer (2007)
Boiler	84	–	70	Cortez and Gomez (1998)
Boiler	–	–	58	RajKumar (2009)
Boiler	72.46	24.89	75.11	Present work.
Combustor	100	45.18		
Heat Exchanger	72.13	48.054		

Table 8
Fan motor energy savings with VSD

Speed Reduction (%)	For 22 kW			For 21 kW		For 19 kW		For 16 kW	
	Power saved (kW)	Energy saved (kWh/yr)	Power saved (kW)		Energy saved (kWh/yr)	Power saved (kW)	Energy saved (kWh/yr)	Power saved (kW)	Energy saved (kWh/yr)
10	4.84	3484.8	4.62		5,322.24	4.18	8125.92	3.52	3548.16
20	9.68	6969.6	9.24		10,644.48	8.36	16,251.84	7.04	7096.32
30	13.42	9662.4	12.81		1457.12	11.59	22,530.96	9.76	9838.08
40	16.06	11,563.2	15.33		17,660.16	13.87	26,963.28	11.68	11,773.44
50	18.26	13,147.2	17.43		20,079.36	15.77	30,656.88	13.28	13,386.24
60	19.58	14,097.6	18.69		21,530.88	16.91	32,873.04	14.24	14,353.92

Table 9
Payback periods for using VSD.

Motor fan power (kW)	Energy saved (kWh/yr)	Cost savings (RM)	Incremental Costs for VSD (RM)	Payback period years
22	14098	3172	23,807	7.5
21	21,531	4844	23,086	4.75
19	32,873	7396	21,643	3
16	14,354	3230	19,479	6

Table 10
Total boiler energy and bill savings for Malaysian industries.

Energy savings (GJ) for savings of				Bill savings (RM) for			
2%	4%	6%	8%	2%	4%	6%	8%
167,978	335,957	503,935	671,913	10,965,250	21,930,501	32,895,751	43,861,002

Total mass of flue gas = 1920 kg/h + 128 kg/h = 2048 kg/h = 0.57 kg/s

Taking the specific heat capacity of flue gas to be 1.1 kJ/kg K, the amount of heat that can be recovered using Eq. (24) as follows:

$$\text{Heat recovered} = \text{mass flow rate} \times \text{specific heat capacity}$$
$$\times \text{temperature drop for flue gas}$$
$$= 0.57 \, \text{kg/s} \times 1.1 \, \text{kJ/kg.K} \times 84.4 \, ^\circ\text{C}$$
$$= 52.9 \, \text{kJ/s} = 52.9 \times 3600 = 190.51 \, \text{MJ/hr}$$

Assuming the heat content in the fuel about 47 MJ/kg, the reduction in fuel usage is

$$\frac{190.51 \, \text{MJ}/h}{50.050 \, \text{MJ/kg}} = 3.806 \, \text{kg}/h$$

$$= \frac{3.806 \, \text{kg}/h}{0.8 \, \text{kg}/L} = 4.757 \, L/h$$

A boiler is operated for about 7920 hr/yr, hence, the fuel saving for one year is $4.757 \, L/\text{h} \times 7920 \, \text{hours/year} = 37,383.29 \, L/\text{year}$

Taking the price of fuel to be RM 1.50/L, the cost saving is calculated below:

$$\text{Cost Saving} = 37,368.29 \, L/\text{year} \times RM1.50/\text{L}$$
$$= RM56,525/\text{year}$$

By taking the cost of heat recovery system in a boiler is around RM 55,500 (www, 2002), payback period is calculated using Eq. (26) as follows:

$$= \frac{RM55,500}{RM56,525}$$

$$\cong 1 \text{ year}$$

Hence, within about 1 yr, the cost of a boiler heat recovery system can be recovered if this method is applied to save energy in a boiler.

Saidur and Lai (2009) reported that 2–8% energy can be saved by enhancing heat transfer rate of flue gases using nanofluids. Energy and bill savings associated with these savings has been shown in Table 9 for total boiler populations in Malaysia.

According to Federation of Manufacturers Malaysia (FMM) directory, there are about 3000 manufacturing industries in Malaysia (FMM, 2006). Using energy audit data from reference (Audit Report, 2007), it has been estimated that about 83,800 GJ of total energy is used by these manufacturing industries. Using this whole use, energy savings for different percentage of savings with the usage of nanofluids is calculated and presented in Table 10.

5. Payback period for flue gas temperature reduction by nanofluids

Using Eq. (26), payback period for using nanofluids and nanosurfaces to reduce the boiler flue gas temperature and associated energy savings can be estimated. Recently authors received the price of nanofluid from a Canadian company (Mknano, 2009) and found that each kg of nanofluids (Al_2O_3) costs about US$100. Normally, few grams of nanofluids are dispersed in a basefluids. These may not cost huge amount. As the cost of nanofluids is very low compared to energy savings, payback period certainly will be very reasonable and the application of these nanofluids and surfaces will be economically very viable.

6. Conclusions

Following conclusions can be drawn from this study:

1. It has been found that heat exchanger and combustor are the main parts that contributed loss of energy.

2. It has been found that exergy efficiency is lower than energy efficiency.

3. It has been found that combustor is the major contributor for exergy destruction in a boiler (shown in Figs. 7 and 8). The overall energy use of the boiler is found to be 19,270.8 kJ/s and exergy destruction is about 10,320 kJ/s. Energy loss is occurred in heat exchanger about 22.5% and but excergy loss is 52%. Flue gas carries 9.2% heat also.

4. It is found that the method of heat recovery from flue gas is one of the effective ways to save energy in a boiler.

5. It has been found that 82,856 kWh of energy and RM18,642 bill can be saved annually using VSD in boilers fan motor system.

6. The study estimated that 671,913 GJ of boilers fuel can be saved for a maximum of 8% energy savings using nanofluids and corresponding bill savings found to be about RM 43,861,002 with economically viable payback period.

   The payback period for heat recovery system in a boiler found to be 1 yr which is economically very viable. The payback period for using VSD with 19 kW motor gives less time for recovery the costs i.e. the payback period in that case is only 3 yr.

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