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 89.21% and 45.48%, 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, Modifications are examined to increase gas-fired steam power plant efficiency by reducing irreversibilities in the steam generator, including Decreasing the fraction of excess combustion air, and/or the stack-gas temperature. Overall-plant energy and exergy efficiencies both increase by 0.19%, 0.37% respectively when the fraction of excess combustion air decreases from 0.4 to 0.15, and by 0.84%, 2.3% when the stack-gas temperature decreases from 137°C to 90°C. 

Keywords—Energy analysis, Exergy analysis, Ambient temperature, Thermal power plant

I. INTRODUCTION

The general energy supply and environmental situation requires an improved utilization of energy sources. Therefore, the complexity of power-generating units has increased considerably. Plant owners are increasingly demanding a strictly guaranteed performance. This requires thermodynamic calculations of high accuracy. As a result, the expenditure for thermodynamic calculation during design and optimization has grown tremendously [1]. The most commonly-used method for evaluating the efficiency of an energy-conversion process is the first-law analysis. However, there is increasing interest in the combined utilization of the first and second laws of thermodynamics, using such concepts as exergy (availability, available energy), entropy generation and irreversibility (exergy destruction) in order to evaluate the efficiency with which the available energy is consumed. Exegetic analysis allows thermodynamic evaluation of energy conservation, because it provides the tool for a clear distinction between energy losses to the environment and internal irreversibilities in the process. A thermal power plant is a good example of the utilization of exegetic analysis. According to energy (first-law) analysis, energy losses associated with the condenser are carried into the environment by the cooling water and are significant because they represent about half of the energy input to the plant. An exergy (second-law) analysis, however, shows that virtually none of the exergy (resource which went into the power plant) is lost in that water. The real loss is primarily back in the boiler where entropy was produced. Thus, it is not reasonable to attempt to take advantage of the energy lost in the condenser [2]. Recently, exergy analysis has become a key aspect in providing a better understanding of the process, to quantify sources of inefficiency, to distinguish quality of energy (or heat) used [1,3–13]. Exergy is defined as the maximum theoretical useful work (or maximum reversible work) obtained as a system interacts with an equilibrium state. Exergy is generally not conserved as energy but destructed in the system. Exergy destruction is the measure of irreversibility that is the source of performance loss. Therefore, an exergy analysis assessing the magnitude of exergy destruction identifies the location, the magnitude and the source of thermodynamic inefficiencies in a thermal system [14].

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 [15] 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 [16]. 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 [17]. In this study, several measures to improve efficiency, primarily developed based on exergy analysis, are considered in this paper. The modifications considered here, which increase efficiency by reducing the irreversibility rate in the steam generator, are

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decreasing the fraction of excess combustion air and/or decreasing the stack-gas temperature. The impact of implementing these measures on efficiencies and losses is investigated. This work aims to identify and assess methods for increasing efficiencies of steam power plants, to provide options for improving their economic and environmental performance.

II. EXERGY ANALYSIS

The process flow diagram for the boiler and power plant is shown in Figure 1 and 2. The process parameters for the power plant and boiler are shown in Table 1 and 2. The following thermodynamic analysis of the power plant will consider the balances of mass, energy, entropy and exergy. Unless otherwise specified, the changes in kinetic and potential energies will be neglected and steady state flow will be assumed. For a steady state process, the mass balance for a control volume system in Figure. 1 can be written as

\[ \sum_{i} \dot{m}_i = \sum_{e} \dot{m}_e \]

(1)

The energy balance for a control volume system is written as

\[ \sum_{i} \dot{E}_i + \dot{Q} = \sum_{\text{out}} \dot{E}'_{\text{out}} + W \]

(2)

The entropy balance for a control volume system is

\[ \sum_{i} \dot{S} + \sum_{T} \frac{\dot{Q}}{T} + S_{\text{gen}} = \sum_{\text{out}} S' + \sum_{T} \frac{\dot{Q}}{T} \]

(3)

The exergy balance for a control volume system is written as

\[ \sum_{i} \dot{E}_{x,i} + \sum_{k} (1 - \frac{T}{T_k}) \dot{Q}_k + \dot{Q} = \sum_{\text{out}} \dot{E}_{x,\text{out}} + W + \dot{E}_{x,d} \]

(4)

Where the exergy rate of a stream is

\[ \dot{E}_{x,i} = \dot{m}_i \dot{e}_x \]

\[ \dot{m}_e = \dot{m}(e_x^{\text{fm}} + e_x^{\text{ch}}) \]

(5)  (6)

The above exergy balance is written in a general form. For the combustion process, the heat input will be included when calculating the chemical exergy of gas. The heat exergy term in Eq. (4) will be used to calculate the exergy loss associated with heat loss to the surroundings. The specific exergy is given by

\[ e_x^{\text{fm}} = (h - h_0) - T_0(S - S_0) \]

(7)

### Table I: OPERATING VALUES OF THE POWER

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass flow rate</td>
<td>16.76 kg/s</td>
</tr>
<tr>
<td>Lower heat value</td>
<td>48500 kJ/kg</td>
</tr>
<tr>
<td>Air mass flow rate</td>
<td>320.7 kg/s</td>
</tr>
<tr>
<td>Maximum temperature in boiler</td>
<td>2000 °C</td>
</tr>
<tr>
<td>Exit temperature from boiler</td>
<td>137 °C</td>
</tr>
<tr>
<td>Feed mass flow rate</td>
<td>1017.5 ton/hr</td>
</tr>
<tr>
<td>Feed pressure</td>
<td>24 MPa</td>
</tr>
<tr>
<td>Feed water inlet temperature</td>
<td>282.5 kg/s</td>
</tr>
<tr>
<td>Steam temperature</td>
<td>540 °C</td>
</tr>
<tr>
<td>Extraction steam pressure</td>
<td>4.48 MPa</td>
</tr>
<tr>
<td>Extraction steam temperature</td>
<td>303 °C</td>
</tr>
<tr>
<td>Extraction steam mass flow</td>
<td>255.8 kg/s</td>
</tr>
<tr>
<td>Reheated steam temperature</td>
<td>540 °C</td>
</tr>
<tr>
<td>Cooling water mass flow rate</td>
<td>10000 kg/s</td>
</tr>
</tbody>
</table>

III. MODELING AND SIMULATION OF BOILER

Fuel of boiler is natural gas including \( CH_4 \cdot C_2H_6 \cdot C_3H_8 \cdot C_4H_{10} \cdot \text{ISO-C}_3H_10 \cdot n-C_3H_{12} \cdot \text{CO}_2 \). The energy and exergy analysis of the cycle has been made using the 'EES' software. The combustion process is assumed to be complete as follows [21]:

\[ \sum_{i=1}^{7} \left[ f_i C_{n_i} H_{m_i} + a f_i \left( n_i + \frac{m_i}{4} \right) O_2 + 3.76 a f_i \left( n_i + \frac{m_i}{4} \right) N_2 \right] + c CO_2 + d N_2 + n_{v,a} + H_2 O \rightarrow \sum (f_i n_i + c) CO_2 + \sum \left( \frac{m_i f_i}{2} + n_{v,a} \right) H_2 O + (\alpha - 1) \sum f_i \left( n_i + \frac{m_i}{4} \right) O_2 \]

\[ + \left[ 3.76 a f_i \left( n_i + \frac{m_i}{4} \right) + d \right] N_2 \]

where \( \alpha \) is the percentage of the excess air, \( f_i \) is the molar fraction of the fuel components parts and \( n_{v,a} \) is the number of moles of the humidity entering the combustion chamber with dry air. The unknown coefficients can be calculated by a molar balance and then the energy and exergy balance of the combustion gases can be performed. For different components of the cycle, the exergy destruction and the exergy efficiency can be obtained by applying exergy balance as follows:

\[ \dot{E}_{x,b} = \dot{m}_i \dot{e}_{x,b}^i + W_{in,b} + \dot{m}_a \dot{e}_{x,a} - \dot{m}_{b} \dot{e}_{x,b} \]

(9)

\[ \sum_{i} \dot{m}_w \dot{e}_{x,w} - \sum_{i} \dot{m}_w \dot{e}_{x,w} = \frac{\dot{m}_f \dot{e}_{x,f}^i + \dot{m}_a \dot{e}_{x,a} + \dot{w}_{in,b}}{\dot{m}_f \dot{e}_{x,f}^i + \dot{m}_a \dot{e}_{x,a} + \dot{w}_{in,b}} \]

(10)

\[ \sum_{i} \dot{m}_w h_w - \sum_{i} \dot{m}_w h_w = \frac{\dot{m}_f \dot{h}_f^i + \dot{m}_a h_a + \dot{w}_{in,b}}{\dot{m}_f \dot{h}_f^i + \dot{m}_a h_a + \dot{w}_{in,b}} \]

(11)

The energy balance equation for calculating adiabatic flame temperature is

\[ \sum N_r (\dot{h}_r^i + h_r - \dot{h}_r^o) = \sum N_p (\dot{h}_p^i + h_p - \dot{h}_p^o) \]

(12)

The destroyed exergy due to combustion process and heat transfer can be expressed as
The second law efficiency of combustion process, heat transfer process of boiler and power plant can be expressed as:

\[
\eta_{II,c} = \frac{\dot{m}_p e_{x,p,adiabatic}}{\dot{m}_f e_{x,f}^{ch} + \dot{m}_a e_{x,a}}
\]

(15)

\[
\eta_{II,ht} = \frac{\sum_{out} \dot{m}_w e_{x,w} - \sum_{in} \dot{m}_w e_{x,w}}{\dot{m}_p e_{x,p,adiabatic} - \dot{m}_p e_{x,p,out,adiabatic}}
\]

(16)

\[
\eta_{II,pp} = 1 - \frac{\dot{E}_{x,d,pp}}{\dot{m}_f e_{x,f}^{ch}}
\]

(17)

IV. RESULTS AND DISCUSSION

Figure 3 shows that the boiler has the most exergy losses in power plant and figure 4 shows that the condenser has the most energy losses in power plant. These figures illustrate the difference between energy and exergy analyses.

Table II shows the result of exergy analyses for the process of boiler. It has been found that the combustion process is the major contributor for exergy destruction followed by heat exchanger of a boiler system.

Table II: The Result of Exergy Analyses for the Boiler

<table>
<thead>
<tr>
<th>Component</th>
<th>Destroyed exergy (MW)</th>
<th>Destroyed exergy to total exergy destroyed (%)</th>
<th>Second law efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler</td>
<td>253.37</td>
<td>34.23</td>
<td>69.94</td>
</tr>
<tr>
<td>Heat transfer process</td>
<td>187.63</td>
<td>45.53</td>
<td>69.42</td>
</tr>
<tr>
<td>Total</td>
<td>441.00</td>
<td>80.45</td>
<td>41.12</td>
</tr>
</tbody>
</table>

V. THE EFFECT OF AMBIENT TEMPERATURE TO POWER PLANT EFFICIENCY

Figure 5 shows the effect of ambient temperature on the energy and exergy efficiencies of the power plant when constant condenser pressure approach is used. Figure 6 shows the same results but when variable condenser pressure approach is taken into account. As shown, the energy efficiency is constant in the case of using constant pressure in the condenser but it decreases with ambient temperature when variable condenser pressure is taken into account. The exergy efficiencies decrease in both cases but the rate of reduction is higher when variable condenser pressure approach is taken into account. Actual data from the power plant agree with variable pressure approach in the condenser.
are likely to be useful to designers of electrical generating stations and can be combined with economic assessments such as the one reported for a coal-fired steam power plant. The present investigation of the changes in steam-generator irreversibility rate and plant efficiency, from decreasing the fraction of excess combustion air and/or decreasing the stack-gas temperature, leads to many useful findings. The results show that decreasing either the fraction of excess combustion air or the stack-gas temperature causes the irreversibility rate in steam generator to decrease, mainly due to the decrease in the irreversibility rate associated with combustion in that device. The improvement in plant exergy efficiencies is 0.37% when the fraction of excess air decreases from 0.4 to 0.15 and 2.3% when the stack-gas temperature decreases from 137°C to 90°C. The improvement when these measures are applied simultaneously is less than the sum of the improvements predicted by applying the measures separately. It would seem to be worthwhile to consider the modifications described in this paper, in both plant retrofits and new designs. The results are likely to be useful to designers of electrical generating stations and can be combined with economic assessments such as the one reported for a coal-fired steam power plant.

VI. CONCLUSION
The present investigation of the changes in steam-generator irreversibility rate and plant efficiency, from decreasing the fraction of excess combustion air and/or decreasing the stack-gas temperature, leads to many useful findings. The results show that decreasing either the fraction of excess combustion air or the stack-gas temperature causes the irreversibility rate in steam generator to decrease, mainly due to the decrease in the irreversibility rate associated with combustion in that device. The improvement in plant exergy efficiencies is 0.37% when the fraction of excess air decreases from 0.4 to 0.15 and 2.3% when the stack-gas temperature decreases from 137°C to 90°C. The improvement when these measures are applied simultaneously is less than the sum of the improvements predicted by applying the measures separately. It would seem to be worthwhile to consider the modifications described in this paper, in both plant retrofits and new designs. The results are likely to be useful to designers of electrical generating stations and can be combined with economic assessments such as the one reported for a coal-fired steam power plant.

Nomenclature

\( e \) \( e \) Specific flow exergy (kJ/kg)
\( E \) \( E \) exergy (kW)
\( h \) \( h \) Specific enthalpy (kJ/kg)
\( \dot{i} \) \( \dot{i} \) Irreversibility rate (kW)
\( \text{LHV} \) \( \text{LHV} \) Low heat value (kJ/kg)
\( \dot{m} \) \( \dot{m} \) Mass flow rate (kg/s)
\( N \) \( N \) Number of moles
\( \dot{P} \) \( \dot{P} \) Pressure (MPa)
\( \dot{Q} \) \( \dot{Q} \) Heat rate (kW)

...