Mathematical Analysis of Boiler by using First and Second law of Thermodynamics

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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 71.6\% and 25\%, respectively. A boiler energy and exergy efficiencies are compared with others work as well. It has been found that combustion chamber is the major contributor for exergy destruction followed by heat exchanger of a boiler system.

Key words: Boiler, Energy, Exergy, Energy efficiency, Exergy efficiency

I. INTRODUCTION

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 hot flue gas losses, radiation losses and, in the case of steam boilers, blow-down losses. To optimize the operation of a boiler plant, it is important to locate where energy loss 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\(^\circ\)C, about 10\textendash}30\% of the heat energy is lost through it. A typical heat balance in a boiler is shown in Fig. 1 (Jayamaha, 2008, Beggs, 2002)

The First Law of Thermodynamics is used to analyze the energy utilization, but it is unable to account the quality aspect of energy. So that exergy analysis is used. 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.

II. GENERAL DESCRIPTION OF BOILER SYSTEM

Exergy is always evaluated with respect to a reference environment. The reference environment is in stable equilibrium, and is a sink or source for heat. T\textsubscript{0}=25\(^\circ\)C as the surrounding temperature, P\textsubscript{0}=100kPa as the surrounding pressure.

III. MATHEMATICAL ANALYSIS

The method used to determine exergy and energy use, energy and exergy efficiencies for boiler. For that boiler decomposes in the combustor and heat exchanger.

A. Analysis on combustor:

1) Energy analysis on combustor:

The combustor in a boiler is usually well insulated that causes heat dissipation to the surrounding almost zero and work is zero. Also, the kinetic and potential energies 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 in coming mass flow rates will be equal to the mass flow rates of the out going mixture.

\[ E_{in} - E_{out} = 0 \]
\[ \dot{E}_{in} = \dot{E}_{out} \]
\[ m_h + m_a - m_h = 0 \]
\[ m_h + m_a = m_h \]

where \( m_h \) = mass flow rate of fuel kg/s, \( m_a \) = mass flow rate of air kg/s, \( h \) = specific enthalpy of air kJ/kg, \( h_f \) = specific enthalpy of fuel kJ/kg

The first law efficiency of combustor

\[ \eta_C = \frac{\dot{m}_p h_p}{\dot{m}_f h_f} \]

2) Exergy 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 To.

\[ X_{in} - X_{out} - X_{destroyed} = 0 \]
\[ m_f \epsilon_f + m_a \epsilon_a - m_p \epsilon_p - X_{D} = 0 \]
\[ X_D = m_f \epsilon_f + m_a \epsilon_a - m_p \epsilon_p \]

Second law efficiency of combustor

\[ \psi_C = \frac{m_f \epsilon_f}{m_f \epsilon_f} \]

B. Analysis of 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.

1) Energy analysis of heat exchanger

A heat exchanger involves no work, negligible kinetic and potential energy. The energy balance as shown in diagram.

\[ E_{in} - E_{out} = 0 \]
\[ \dot{E}_{in} = \dot{E}_{out} \]
\[ (m_h h_p + m_h h_l) - (m_h h_p + m_h h_l) = Q \]
\[ Q = m_f (h_p - h_l) - m_p (h_p - h_l) \]

First law efficiency of heat exchanger

\[ \eta_H = \frac{m_f (h_p - h_l)}{m_p (h_p - h_l)} \]

The overall efficiency of boiler is given by

\[ \eta_B = \frac{m_f (h_p - h_l)}{m_f h_f} \]

Table 1: Input Data (DOSH-2008)

<table>
<thead>
<tr>
<th>Substance</th>
<th>Mass Flow rate kg/s</th>
<th>Temperature °C</th>
<th>Enthalpy kJ/kg</th>
<th>Entropy kJ/kg °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>4.125</td>
<td>126.85</td>
<td>400.98</td>
<td>1.9919</td>
</tr>
<tr>
<td>Fuel</td>
<td>0.275</td>
<td>1243.99</td>
<td>50050</td>
<td>2</td>
</tr>
<tr>
<td>Hot products</td>
<td>4.40</td>
<td>250</td>
<td>3504</td>
<td>7.0716</td>
</tr>
<tr>
<td>Water</td>
<td>4.22</td>
<td>100</td>
<td>419.15</td>
<td>1.307</td>
</tr>
<tr>
<td>Steam</td>
<td>4.22</td>
<td>185.33</td>
<td>2782.73</td>
<td>6.546</td>
</tr>
<tr>
<td>Flue gases</td>
<td>4.4</td>
<td>212.57</td>
<td>361.44</td>
<td>1.9</td>
</tr>
</tbody>
</table>

IV. Results and Discussion

A. Analysis on combustor

1) Energy use of combustor

\[ E_{in} = m_f h_f + m_a h_a \]

where \( E_{in} \) = 15416.34 kJ/s

2) Exergy destruction of combustor

In Exergy destruction 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 and that there is no work interaction involved and the kinetic and potential energies are negligible.

\[ \eta_E = \frac{m_f \epsilon_f}{m_f \epsilon_f} = 44.87\% \]

B. Energy use in the heat exchanger

\[ Q = m_f (h_p - h_l) - m_p (h_p - h_l) \]

where \( Q \) = 3856 kJ/s

First law efficiency of heat exchanger

\[ \eta_H = \frac{m_f (h_p - h_l)}{m_p (h_p - h_l)} = 71.65\% \]

Overall efficiency of boiler

\[ \eta_B = \frac{m_f (h_p - h_l)}{m_f h_f} = 71.6\% \]

Fig. 4: Heat Exchanger Schematic diagram

Fig. 5: Grassman Diagram for combustor
C. Exergy destruction in the heat exchanger

\[ X_d = m_1(\epsilon_f - \epsilon_i) + m_2(\epsilon_f - \epsilon_e) \]
\[ = 3662 \text{ kJ/s} \]

Second Law efficiency of heat exchanger

\[ \psi_H = \frac{m_1(\epsilon_f - \epsilon_i)}{m_1(\epsilon_f - \epsilon_e)} \]
\[ = 47.92\% \]

The overall heat balance for boiler

\[ X_B = X_D + X_H \]
\[ = 6658 + 3662 = 10320 \text{ kJ/s} \]

Overall exergy efficiency of boiler

\[ \psi_B = \frac{m_1(\epsilon_f - \epsilon_i)}{m_1 \epsilon_f} \]
\[ = 25\% \]

| Combustor | 15416.34 | 6658 | 100 | 44.87 |
| Heat exchanger | 3856 | 3662 | 71.65 | 47.92 |
| Boiler | 19272.34 | 10320 | 71.6 | 25 |

Table 2: Result

Fig. 6: Grassman diagram for heat exchanger

Section sets of parameters by Minitab software and find NOx emission for those sets of parameters. NOx for those sets are given in table 2.

V. CONCLUSION

In this study following conclusion are drawn:

- It has been found that heat exchanger and combustor are the main parts that contributed loss of energy
- Combustor is the major contributor for exergy destruction in a boiler as shown in Fig-5 and Fig-6.
- The exergy efficiency is lower than the energy efficiency.

REFERENCES