Boiler Thermal Efficiency Determination At Steady State For Two Different Conditions

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Abstract— This paper presents an experiment work to determine the thermal efficiency of boiler at steady state for two different conditions, and measure the components of flue gas stream at the same conditions. During the experiment, there were two steady states conditions. The first condition was estimated after 86 minute from the beginning of the experiment, during this period each of the air and the gas flow rates was adjusted to (550 & 50) L/min respectively. After reaching the first steady state, both of Q_{air} and Q_{gas} were increased to (900 and 75) L/min respectively. The second steady state condition was estimated after 20 minutes from the end of the first steady state. The water flow rate during the experiment was constant, and the flow was adjusted on 10L/min. The performed results indicate that the thermal efficiency of boiler decreases by approximately 10 percent when the operation conditions are changed from the first set to the second. The increase in the amount of excess air in the second condition, and the increase in the flue gas temperature are the possible reasons.

Keywords— Boiler, Thermal Efficiency, Excess air, Combustion.

I. INTRODUCTION

A boiler can be defined as the equipment that can be used to produce steam through boiling the water. Scientifically, boilers are defined as a device that converts the energy stored in the fuel as a chemical energy into heat energy (hot water). In some types of boilers, technically steam is produced as a result of heat transfer of heat energy of hot gases to water when the operation involved no firing. Boilers have been used for more than 150 years. Comparing to today, boilers have been developed significantly in the following aspects: size, variety, reliability, complexity and flexibility [4] [7].

Recently, boilers usage extended to include some developing countries such as china and India as a result of fast industrialization. There are several types of boilers and it can be classified according to (water, fire) streams and circulations, type of fuel used, (temperature and pressure) applied, and steam conditions [4] [1] [5].

Modified boilers are found to be capable to have thermal efficiency in the range of 80% to 90% depending on the fuel and required amount of access air, which can be useful to limit the flame temperature, to prevent melting boiler tubes. The flue gas temperature is usually higher than the flame temperature and it is regularly used to preheat the inlet air by having the inlet air entering through it prior to using it, and that is to raise the thermal efficiency of the boiler [6]. However, as any thermodynamic system heat loss can be happening about (%1.5 - %2.5) [2] [3].

The economic gas fired horizontal boiler type was used in this experiment to raise the temperature of the water, by converting the chemical energy in the fuel to the heat energy in the heated water [3].

II. EXPERIMENTAL RIG DIAGRAM

Figure 1 shows an overall description diagram for the equipment used, boiler, along with the auxiliary units. The diagram shows that a burner is attached prior to the boiler inlet, and it is equipped with a temperature sensor. At the boiler exit, the flue gas goes directly to the stack; a probe is attached to analyse the exhaust gases concentrations. Water is circulated to control the heat inside the boiler.

![Figure 1: A rig diagram showing the equipment used](http://www.ijettjournal.org)

Where:

- T1= Flue Gas Temperature (°C)
- T2= Water Outlet Temperature (°C)
- T3= Jacket Temperature (°C)
- T4= Water Inlet Temperature (°C)
- T5= Air and Gas Inlet Temperature (°C)
III. EXPERIMENTAL WORK

The air and natural gas were injected to the burner via a series of pipelines and at regular flow rates, the combustion of the fuel and air were occurred after the igniting. Then, the water was started to flow into the boiler through a series of pipelines at steady flow rate and room temperature. Inside the boiler’s tank, the water temperature started to increase gradually. The water pipe and the heat of combustion inside the tank were in direct contact. The hot water from the boiler was rejected through a water pipe and the heat of combustion inside the tank were in direct contact.

The hot water from the boiler was rejected through a pipe to drain, and the flue gas was released to outside the unit through the stack. During the boiler operation, Kane 940 analyser was used to measure the concentrations of CO₂, CO and NOₓ in the flue gas via a probe. The probe was attached to the stack and the gas samples were sent to gas sampling and conditioning unit before the gas samples were sent to gas sampling and conditioning unit through the stack. During the boiler operation, the (inlet and outlet water, flue gas, jacket and gas & air inlet). Then, the measured temperatures were displayed in digital screen (experimental Rig diagram).

Gas sampling and conditioning unit, was to protect the analyser from harmful effects that can be caused by: corrosion, moisture, high pressure, high temperature, and organizing the flow. Furthermore, there were five K-type thermocouples connected to the boiler, where used to measure the temperature of the (inlet and outlet water, flue gas, jacket and gas & air inlet). Then, the measured temperatures were displayed in digital screen (experimental Rig diagram).

IV. EXPERIMENTAL DATA

Two sets of results are recorded. Table one illustrates the concentration of combustion products in percentages for O₂ and CO₂, and in ppm for CO, NO and NOₓ in regard to time for multi number of runs (7 runs are provided from a total of 54). Furthermore, table 2 lists the boiler outlet and inlet temperatures in (˚C) with time for the first and latest couple of runs.

Table 1: Concentration of combustion products

<table>
<thead>
<tr>
<th>Run</th>
<th>Time</th>
<th>O₂ (%)</th>
<th>CO (%)</th>
<th>CO₂ (ppm)</th>
<th>NO (%)</th>
<th>NOₓ (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12:43.4</td>
<td>21</td>
<td>0</td>
<td>3200</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>12:43.4</td>
<td>21</td>
<td>0</td>
<td>3200</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>12:45.6</td>
<td>6.9</td>
<td>168</td>
<td>7.7</td>
<td>27</td>
<td>28</td>
</tr>
<tr>
<td>4</td>
<td>12:48.0</td>
<td>3.5</td>
<td>860</td>
<td>9.9</td>
<td>48</td>
<td>50</td>
</tr>
<tr>
<td>5</td>
<td>12:48.1</td>
<td>3.5</td>
<td>860</td>
<td>9.9</td>
<td>48</td>
<td>50</td>
</tr>
<tr>
<td>6</td>
<td>12:50.1</td>
<td>1.3</td>
<td>3203</td>
<td>11.2</td>
<td>52</td>
<td>54</td>
</tr>
<tr>
<td>7</td>
<td>12:52.1</td>
<td>2.8</td>
<td>1027</td>
<td>10.2</td>
<td>62</td>
<td>65</td>
</tr>
</tbody>
</table>

Table 2: Boiler outlet and inlet temperatures, (T in ˚C)

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>T₁</th>
<th>T₂</th>
<th>T₃</th>
<th>T₄</th>
<th>T₅</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>16.2</td>
<td>13.6</td>
<td>13.6</td>
<td>13.0</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>16.2</td>
<td>13.6</td>
<td>13.6</td>
<td>13.0</td>
<td></td>
</tr>
<tr>
<td>6179</td>
<td>89.0</td>
<td>58.5</td>
<td>71.3</td>
<td>13.2</td>
<td></td>
</tr>
<tr>
<td>6180</td>
<td>88.8</td>
<td>58.5</td>
<td>71.3</td>
<td>13.2</td>
<td></td>
</tr>
</tbody>
</table>

During the experiment, the temperature at both operation conditions was reached a semi steady state rather than steady state. The turbulence in the air flow inside the boiler was considered as a possible reason for reaching the semi steady state. Table 3, on the other hand, sums the main data collected for both conditions.

Table 3: Main data collected for both conditions

<table>
<thead>
<tr>
<th>Duration</th>
<th>Q₆₇</th>
<th>Q₈₇</th>
<th>Q₉₇</th>
<th>T₁  (˚C)</th>
<th>T₂  (˚C)</th>
<th>T₃  (˚C)</th>
<th>T₄  (˚C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>86 min</td>
<td>10</td>
<td>550</td>
<td>50</td>
<td>70.4</td>
<td>48.8</td>
<td>61.7</td>
</tr>
<tr>
<td>2</td>
<td>20 min</td>
<td>10</td>
<td>900</td>
<td>75</td>
<td>92.1</td>
<td>58.5</td>
<td>70.4</td>
</tr>
</tbody>
</table>

Where Q₆₇, Q₈₇ and Q₉₇ are water, air and gas flow rates in (L/min) respectively.

V. BOILER EFFICIENCY CALCULATIONS

Heat produced by combustion of the gas (q₉fuel) can be calculated from

\[ q_{fuel} = C.V \times Q_{fuel} \]  \hspace{1cm} (1)

Where C.V is the calorific value of methane (C.V = 34.84 MJ/m³)

Values of q₉fuel are 28.91kJ/sec and 43.55 kJ/sec for 1st and 2nd conditions respectively.

Heat taken up by the water (q₉water) can be calculated from

\[ q_{water} = c_p * m * \Delta T_{water} \]  \hspace{1cm} (2)

Where \( CP \) of water is 4.18 KJ/Kg.K, and \( m \) is the mass of the water.

Values of q₉water are 24.84 kJ/sec and 31.57 kJ/sec for 1st and 2nd conditions respectively.

The efficiency of boiler (η) is calculated from this equation

\[ \eta = \frac{q_{water}}{q_{fuel}} \]  \hspace{1cm} (3)

\( \eta \) is 85.92% and 72.49 % for 1st and 2nd conditions respectively.
VI. HEAT LOSSES

To calculate the overall heat loss for both conditions, it is necessary to account for the heat taken away in the flue gas according to the following equation

\[ q_{f.g} = cp_{f.g} \times m \times \Delta T_{water} \] (4)

Values of \( q_{f.g} \) are 0.7 kJ/sec and 0.45 kJ/sec for 1st and 2nd conditions respectively.

The second step is to carry on an overall energy balance equation according to equation number 5

\[ q_{fuel} = q_{f.g} + q_{water} + q_{loss} \] (5)

Values of \( q_{loss} \) are 3.37 kJ/sec and 11.53 kJ/sec for 1st and 2nd conditions respectively.

The energy balance of the boiler indicated that the percentage (as shown in figure 2) of heat loss from the system increased considerably between 1st condition and 2nd condition. Heat loss from the first condition estimated with 11.65%, while the heat loss from the second condition accounted for 26.47%. The increase in the flue gas temperature at the second condition can be considered as one reason for raising the percentage of heat loss, where the increase in combustion rate leads to increase the radiation and convection heat losses.

VII. THEO. AIR & EQUIVALENT RATIO

For condition 1, the theoretical air value can be calculated based on the chemical reaction equation below

\[ \text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} \]

The combustion equation indicates that the complete combustion requires to 100 L of \( \text{O}_2 \), and where air is 21% oxygen, the amount of theoretical air which require to complete burning is 476.19L. The amount of excess air is

\[ \text{Excess air} = \text{supplied air} - \text{theoretical air} \] (6)

Where the theoretical air is 476.19 L, and supplied air is 550 L. Then the excess air will equal to 15.5 %

Furthermore, the Equivalent ratio equals to the ratio of theoretical by excess air, and that is 0.865 <1 then the fuel is lean.

Similarly, for condition 2, the amount of theoretical air required to complete burning is 714.28 L. Excess air = 26 %, and the Equivalent ratio equals to 0.793.

VIII. QUANTITY OF COMBUSTION PRODUCTS

The quantities of each compound in the products after combustion, \( \text{CO}_2 \), \( \text{H}_2\text{O} \), \( \text{O}_2 \) and \( \text{N}_2 \), can be estimated by a simple material balance calculation.

Figures 3 and 4 below show the percentage of combustion products during the operation conditions. The percentages of \( \text{CO}_2 \), \( \text{O}_2 \) and \( \text{N}_2 \) are found to be increased approximately by 2% when a change in the operation conditions occur, whilst the proportion of water vapor remains constant during the experiment (17%).

IX. CONCLUSION

This phenomenon explained as there was a turbulent in the air flow inside the boiler. Moreover, the energy balance of the boiler’s system indicated that there were considerable heat losses, especially in the second operation condition. The heat loss in first
condition calculated equal to 3.37 KJ/sec, while in second operation conditions it was equal to 11.53 KJ/sec. In addition, the experimental results showed that the increase in the amount of excess air affected considerably on decreasing the rate of CO emissions. However, this increase in the amount of inserted air was caused to increase the emissions of NOx and CO$_2$.

REFERENCES