Exergy and Energy Analysis of CFPP

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Abstract. Energy and exergy analysis of Pulverized Coal Fired Subcritical Power Plant (CFPP) performed to assess power plant performance and identify major losses both energy and exergy term. It’s found that, based on energy analysis, major losses occur in condenser, moisture in coal and steam turbine. While exergy analysis result that most exergy losses and destruction was in boiler and feedwater heater. Energy efficiency of boiler on 250MW, 300MW and 380MW was 68.56%, 69.56% and 72.42% respectively while exergetic efficiency was 52.81%, 56.33% and 57.39% respectively.

1. Introduction
Indonesian Electricity consumption was 213,800 GWH per year (2016). Most of electricity (+ 55.6%) generate on coal-fired power plant that requires 85 million ton of coal per year. Indonesian coal reserve in 2017 was 28,457.29 million tons which will run out in next 72 years [8]. Audit should take place to identify energy losses and potential improvement in efficiency to extend coal availability.

Currently energy audit in CFPP perform based on energy calculation to identify energy losses, however fail to identify potential area of efficiency improvement. Exergy analysis performed based on 2nd law of thermodynamic of irreversibility, to finding component performance and identify possible area to improve efficiency.

Kalimuthu et.al [1] research energy, exergy and environment analysis of 400MW Sub Critical Pressurized Pulverized Combine Cycle (PPCC). Their result show that energetic and exergy efficiency was 42.44% and 38.94% respectively. Maximum energy losses were observed in Cooling water (24%) and maximum exergy destruction in combustor (32%).

Cuneyt et.al [2] observe exergy and thermo-economy on 150 MW CFPP in Turkey. Their result show power plant exergy efficiency was 39.89% and equipment with highest potential improvement was boiler.

Behbahaninia et.al [3] develop method of exergy auditing on steam boiler, based on ASME PTC 4.1. limit their study on exergy loss due to dry gas, unburnt coal and radiation through boiler wall. while largest exergy destruction inside the boiler which is 38% of total exergy input.
Rana and Mehta [4] research energy-exergy analysis on 22MW full condensing steam turbine. Their result show that energy efficiency for 80% MCR was 30.66% while exergetic efficiency was 76.82%.

2. Method
This study utilizes thermal loss method base on first law thermodynamic, as used in ASME PTC [5], combine with exergy analysis base on the second law of thermodynamic. To combine these methods,
study starts with energy analysis then exergy analysis on each main equipment of power plant. Energy analysis on the boiler perform based on ASME PTC 4. Exergy analysis of boiler carried out by exergy calculation base on exergetic efficiency, include exergy loss and exergy destruction in boiler [3]. Energy analysis of steam turbine performs base on ASME PTC 6. Exergy analysis of turbine done by analysing exergy flow of steam turbine [4].

Following nomenclature use in this report:

\[ Q = \text{energy} \]
\[ W = \text{Work done by turbine} \]
\[ \dot{m}_i = \text{mass flow} \]
\[ T_s = \text{Surface Temperature} \]
\[ \eta = \text{efficiency} \]
\[ \eta_{\text{ex}} = \text{exergetic efficiency} \]
\[ h_i = \text{enthalpy at point } i \]
\[ s_i = \text{entropy at point } i \]

2.1. Description of Coal Fired Power Plant

The Power plant was located in Java island with install capacity 400MWe generated from HP, IP and LP turbine. This plant uses pulverized coal-fired boiler with main-steam maximum temperature 538°C and pressure 165.8 bar. The plant was equipped with six closed feed water heater, one open feed water heater, and steam surface condenser. Schematic as shown in Fig. 1.

![Schematic diagram of 400MW Sub Critical Coal Fired Power Plant](image)

Figure 1. Schematic diagram of 400MW Sub Critical Coal Fired Power Plant

2.2. Energy analysis

Energy analysis method was develop based on energy and mass balance. In boiler energy balance calculate by formula.

\[ \Sigma Q_{\text{in}} = \Sigma Q_{\text{out}} + Q_{\text{loss}} \]  
Where \( Q_i = \dot{m}_i \times h_i \) for water-steam, \( Q_i = HV \) for fuel, and \( Q_i = \dot{m}_i \times C_p_l \) for gas.

Losses in energy analysis was delta of energy in and energy out of control volume. Boiler energy analysis can be done by the direct and indirect methods. Refer to Fig. 1, direct method employed energy and mass balance of boiler base on first law of thermodynamic.

\[ Q_{\text{in}} = \dot{m}_{22} \cdot h_{22} + \dot{m}_{35} \cdot h_{35} + \dot{m}_{34} \cdot HV_{\text{coal}} + \dot{m}_3 \cdot h_3 + \dot{m}_{24} \cdot h_{24} + \dot{m}_{23} \cdot h_{23} \]  
\[ Q_{\text{out}} = \dot{m}_1 \cdot h_1 + \dot{m}_4 \cdot h_4 + \dot{m}_{25} \cdot h_{25} + \dot{m}_{37} \cdot C_{P37} \]

Where \( HV_{\text{coal}} \) was heating value of coal and \( C_{P37} \) was specific heat of flue gas. Indirect method calculate loss in boiler base on ASME PTC 4. This study focuses on unburnt losses (\( L_{UB} \)), dry gas
(\(L_{DG}\)), moisture (\(L_{WA}, L_{WC}\)) and radiation convection (\(L_{SRC}\)). Other losses were present as unaccounted loss. Losses calculated by formula as shown in Table 1.

\[
Q_{loss} = L_{UB} + L_{DG} + L_{WA} + L_{WC} + L_{SRC} + L_{UA}
\]

(4)

| Losses                              | Formula                                                                 |
|-------------------------------------|-------------------------------------------------------------------------|
| Dry Gas Losses                      | \(L_{DG} = 0.0024 \times \dot{m}_{\text{dry, gas,D}} \times (T_{FG} - T_{c})\) |
| Moisture losses from Air            | \(L_{WA} = \dot{m}_{H_{2}O,fuel} \times (h_{\text{steam} @ 1\text{psi},T_6} - h_{\text{water} @ 1\text{psi},T_6})\) |
| Moisture losses from Coal Surface  | \(L_{WC} = \dot{m}_{H_{2}O,air,0} \times \dot{m}_{\text{Dry air}} \times h_{\text{water vapor} @ T_{38}}\) |
| Radiation and convection losses    | \(L_{SRC} = C_1 \cdot \sum(H_{CaZ} + H_{rAz}) \cdot A \cdot (T_a - T_0)\) |
|                                     | \(H_{CaZ} = 0.847 + 2.367 \times 10^{-3} \times T_D + 2.94 \times 10^{-6} \times T_D^2 + 1.37 \times 10^{-9} \times T_D^3\) |
|                                     | \(C_1 = 1 \text{ Btu/hr} \quad \text{for US Customary Unit and} \quad C_1 = 0.293 \text{ for SI unit.}\) |

Turbine energy analysis perform based on ASME PTC 6 [6] that energy of turbine can be calculated by enthalpy drop each stage of turbine. Formula to calculate energy balance as shown in Table 2

\[
Q_{in} = W_T + Q_{out} + Q_{loss}
\]

(5)

| Section     | Energy Balance | Exergy Balance |
|-------------|----------------|----------------|
| HP Turbine  | \(m_1, h_1 = W_{HPT} + m_1h_1 + Q_{loss}\) | \(E_1 = E_3 + W_{HPT} + E_{D,HPT}\) |
| IP Turbine  | \(m_4, h_4 = W_{IPT,1} + m_4h_4 + Q_{loss}\) | \(E_4 = E_5 + E_7 + W_{IPT} + E_{D,IPT}\) |
|             | \((m_4 - m_5), h_5 = W_{IPT,2} + (m_4 - m_5), h_5 + Q_{loss}\) | |
| LP Turbine  | \(m_7, h_7 = W_{LPT,1} + m_7h_7 + Q_{loss}\) | \(E_7 = E_8 + E_9 + E_{10} + E_{11} + E_{12} + W_{LPT} + E_{D,LPT}\) |
|             | \((m_7 - m_8), h_8 = W_{LPT,2} + (m_7 - m_8), h_8 + Q_{loss}\) | |
|             | \((m_7 - m_9 - m_9), h_9 = W_{LPT,3} + (m_7 - m_8 - m_9), h_9 + Q_{loss}\) | |
|             | \((m_7 - m_9 - m_10), h_{10} = W_{LPT,4} + (m_7 - m_8 - m_9), h_{10} + Q_{loss}\) | |

Energy loss in the Condenser is the difference between steam energy in and condensate energy out. Energy analysis on feed water heater (FWH) based on energy balance both hot and cold side. The formula for energy equation for Condenser and FWH based on Equation-1 as shown in Table 3

| Section     | Energy Balance Equation | Exergy Balance Equation |
|-------------|-------------------------|-------------------------|
| LPH1        | \(m_{11}, h_{11} + m_{14}, h_{14} + m_{30}, h_{30} = m_{15}, h_{15} + m_{31}, h_{31} + Q_{loss}\) | \(E_{11} + E_{14} + E_{30} = E_{15} + E_{31} + E_D\) |
| LPH2        | \(m_{10}, h_{10} + m_{15}, h_{15} + m_{29}, h_{29} = m_{16}, h_{16} + m_{30}, h_{30} + Q_{loss}\) | \(E_{10} + E_{15} + E_{29} = E_{16} + E_{30} + E_D\) |
| LPH3        | \(m_9, h_9 + m_{16}, h_{16} = m_{17}, h_{17} + m_{29}, h_{29} + Q_{loss}\) | \(E_9 + E_{16} = E_{17} + E_{29} + E_D\) |
| Deaerator   | \(m_8, h_8 + m_{17}, h_{17} + m_{28}, h_{28} = m_{18}, h_{18} + Q_{loss}\) | \(E_8 + E_{17} + E_{28} = E_{18} + E_D\) |
| HPH5        | \(m_6, h_6 + m_{19}, h_{19} + m_{27}, h_{27} = m_{20}, h_{20} + m_{28}, h_{28} + Q_{loss}\) | \(E_6 + E_{19} + E_{27} = E_{20} + E_{28} + E_D\) |
| HPH6        | \(m_5, h_5 + m_{26}, h_{26} + m_{20}, h_{20} = m_{21}, h_{21} + m_{27}, h_{27} + Q_{loss}\) | \(E_5 + E_{26} + E_{20} = E_{21} + E_{27} + E_D\) |
2.3. Exergy analysis

Exergy is the maximum work obtained from the system to the point of equilibrium between the system and the environment (dead state). Exergy analysis perform based on mass and exergy balance, represent as following mathematical model:

\[ \dot{E}_{\text{Fuel}} = \dot{E}_{\text{Out}} + \dot{E}_{\text{Product}} + \dot{E}_{\text{Destruction}} \]  

(6)

Exergy rate \( \dot{E}_i \) as function of mass flowrate \( \dot{m}_i \) and specific exergy \( \varepsilon_i \).

\[ \dot{E}_i = \dot{m}_i \times \varepsilon_i \]  

(7)

Where \( \dot{m}_i \) was mass flow and \( \varepsilon_i \) was specific exergy.

\[ \varepsilon_{\text{ph},i} = h_i - T_0 \cdot s_i \]  

(8)

\[ \varepsilon_{\text{ph}} = C_p \times \left( T - T_0 - T_0 \cdot \ln \left( \frac{T}{T_0} \right) \right) + R \cdot T \cdot \ln \left( \frac{P}{P_0} \right) \]  

(9)

\[ \varepsilon_{\text{CH}_4} = 1.009 + \frac{0.131 \cdot O^2 + 0.16 \cdot W^2}{100 - (A^2 + W^2)} \]  

(10)

Boiler exergy loss and destruction analysis perform based exergy balance of boiler [3]. Exergy loss in boiler includes losses due to flue gas (\( L_1 \)), unburnt coal (\( L_2 \)), incomplete combustion (\( L_3 \)) and radiation loss (\( L_4 \)). Exergy destruction was occurred in boiler (\( E_{D1} \)) and gas air heater (\( E_{D2} \)). Equation related these losses as shown in Table 4.

| Table 4. Exergy Loss and Destruction in Boiler |
|---------------------------------------------|
| Point of Losses                             | Formula                                                                 |
| Dry Flue Gas (\( E_{L1} \))               | \( \frac{m_{G,38}}{M_{G,38}} \times \varepsilon_{ch,38} + m_{G,38} \times \varepsilon_{ph,38} \) |
| Moisture (\( E_{L2} \))                    | \( \frac{m_{G,38}}{M_{G,38}} \times (\varepsilon_{ch} + RT_0 \times x_{CH} \ln x_{CH}) \) |
| Incomplete Combustion (\( E_{L3} \))       | \( \frac{C_O}{C_O + C_O^2} (\varepsilon_{CO} - \varepsilon_{CO_2}) G_b \times m_{\text{fuel}} \) |
| Radiation Loss (\( E_{L4} \))              | \( Q_{\text{radiation loss}} \times \left( 1 - \frac{T_0}{T} \right) \) |
| Boiler (\( E_{D1} \))                      | \( m_F - m_P \times \left( \frac{m_{G,37}}{M_{G,37}} \times \varepsilon_{ch,37} + m_{G,37} \times \varepsilon_{ph,37} \right) \) |
| Gas Air Heater (\( E_{D2} \))              | \( \left( \frac{m_{G,37}}{M_{G,37}} \times \varepsilon_{ch,37} + m_{G,37} \times \varepsilon_{ph,37} \right) + m_{36} \times \varepsilon_{ph,36} \) |

Turbine exergy destruction is calculated based on exergy input, output and turbine power [4] using equation as shown in Table 2. Condenser exergy loss was delta of exergy flow-in to condenser and exergy of condensate flow-out from condenser. Feedwater heater exergy calculated based on exergy balance as shown in Table 3.

3. Calculation

Mathematic model was developed using MATLAB software to perform energy and exergy calculation using equation from Table 1 to Table 4. Analysis perform at Generator gross output 250MW, 300MW and 380MW, use mixed coal with heating value 4,168,44 kCal/kg; 4,185,13 kCal/kg and 4,218,27 kCal/kg respectively. Plant operation data for study as shown in Table 5.

Result of energy and exergy analysis as shown in Table 6 to Table 9. Efficiency of Turbine calculate by isentropic energy capture compare to measured energy capture.
Isentropic energy capture
\[ W_{\text{HPT}} = m_1 \times (h_1 - h_3) = 220.63 \times (3,424.44 - 2,968.00) = 100,643.16 \, \text{kJ/s} \]

Measured energy capture
\[ W_{\text{HPT}} = m_1 \times (h_1 - h_3) = 220.63 \times (3,424.44 - 3,084.26) = 75,052.08 \, \text{kJ/s} \]
\[ \eta_{\text{HPT}} = \frac{E_{\text{power}}}{E_{\text{in}}} = \frac{75,052.08}{100,643.16} = 74.57\% \]

Table 5. Operating Data

| Pipe No | Equipment  | Flowrate (kg/s) | Pressure (bar) | Temperature (°C) |
|---------|------------|-----------------|----------------|------------------|
|         |            | 380  | 300  | 250  | 380  | 300  | 250  | 380  | 300  | 250  |
| 1       | Main Steam | 338.7173 | 263.4800 | 220.6259 | 165.8155 | 157.5800 | 137.0500 | 536.8 | 534.4 | 535.2 |
| 2       | HPH7       | 54.9837 | 35.1800 | 34.1111 | 42.8092 | 31.9500 | 27.7085 | 311.8 | 292.1 | 334.3 |
| 3       | Cold Reheat | 283.7336 | 228.3000 | 186.5148 | 43.6533 | 33.6000 | 27.7085 | 354.1 | 332.9 | 334.3 |
| 4       | Hot Reheat | 298.6401 | 234.4800 | 189.5529 | 40.3394 | 32.5700 | 27.7085 | 537.6 | 536.2 | 534.6 |
| 5       | HPH6       | 22.0214 | 13.6800 | 13.7167 | 19.5535 | 14.9500 | 12.5351 | 433.2 | 429.3 | 429.0 |
| 6       | HPH5       | 140.1095 | 35.1800 | 89.3556 | 8.3557 | 6.4000 | 5.3843 | 307.9 | 302.1 | 303.2 |
| 8       | Deaerator  | 40.1100 | 7.0600 | 6.9400 | 4.7728 | 3.6700 | 3.0845 | 249.5 | 249.9 | 252.3 |
| 9       | LPH3       | 12.3656 | 17.4900 | 6.9387 | 2.6977 | 2.0900 | 1.7585 | 209.2 | 210.1 | 212.5 |
| 10      | LPH2       | 21.8203 | 17.6400 | 14.5735 | 1.5036 | 1.2100 | 1.0721 | 111.5 | 108.9 | 110.9 |
| 11      | LPH1       | 2.7335 | 10.3200 | 0.4633 | 1.0075 | 0.3300 | 0.9740 | 99.8 | 74.9 | 104.8 |
| 12      | COND       | 109.5892 | 133.1100 | 57.5652 | 0.0837 | 0.0800 | 0.0723 | 43.0 | 42.4 | 40.0 |
| 23      | SH Spray   | 14.9065 | 4.6184 | 4.1294 | 168.2672 | 154.1912 | 131.9940 | 248.5 | 240.3 | 224.6 |
| 24      | RH Spray   | 8.7633 | 6.1755 | 3.0381 | 168.2672 | 154.1912 | 131.9940 | 248.5 | 240.3 | 224.6 |
| 25      | Auxiliary  | 4.2941 | 5.7468 | 5.5819 | 9.1900 | 14.8624 | 10.9984 | 536.8 | 534.4 | 535.2 |
| 34      | Coal Flow  | 66.6792 | 55.2782 | 46.7841 | - | - | - | - | - | - |
| 35      | Air flow   | 482.9169 | 394.6418 | 334.5694 | 41.0180 | 41.0180 | 41.0180 | 278.3 | 278.3 | 278.3 |

Exergy of HP Turbine calculate by
\[ E_{\text{in}} = m_1 \times (h_1 - T_0 \cdot s_1) = 220.63 \times (3,424.44 - 304.00 \times 6.5289) = 317,624.45 \, \text{kJ/s} \]
\[ E_{\text{out}} = m_1 \times (h_3 - T_0 \cdot s_3) = 220.63 \times (3,084.26 - 304.00 \times 6.7278) = 229,232.09 \, \text{kJ/s} \]
\[ E_{\text{turbine power}} = W_{\text{HPT}} = 75,052.08 \, \text{kJ/s} \]
\[ E_{\text{des}} = E_{\text{in}} - E_{\text{out}} - E_{\text{turbine power}} = 317,624.45 - 229,232.09 - 75,052.08 = 14,478.39 \, \text{kJ/s} \]
\[ \eta_{\text{II}} = \frac{E_{\text{power}}}{E_{\text{in}}} = \frac{75,052.08}{317,624.45} = 23.63\% \]

Similar calculation performs for all turbines. Result of turbine energy and exergy analysis as shown in table 6.

Table 6. Energy and Exergy of Steam Turbine

| SEGMENT | ENERGY CAPTURED [kJ/s] | EXERGY CAPTURED [kJ/s] |
|---------|------------------------|------------------------|
|         | 380MW      | 300MW      | 250MW      | 380MW      | 300MW      | 250MW      |
| HP Turbine | 129,936.70 | 114,749.49 | 100,643.16 | 115,955.97 | 101,762.56 | 88,395.12 |
| IP Turbine | 145,653.29 | 120,132.23 | 98,306.23  | 139,560.02 | 113,565.29 | 94,475.38 |
| LP Turbine | 197,121.66 | 147,434.04 | 129,167.46 | 199,254.05 | 151,032.61 | 130,863.15 |
| Total      | 472,711.64 | 382,315.76 | 328,116.85 | 454,770.04 | 366,360.46 | 313,733.65 |
| Generator Output | 388,995.85 | 303,614.36 | 254,528.52 | 388,995.85 | 303,614.36 | 254,528.52 |
| Efficiency * | 82.29%     | 79.41%     | 77.57%     | 85.54%     | 82.87%     | 81.13%     |
Loss/ Destruct | 83,715.79 | 78,701.40 | 73,588.33 | 65,774.20 | 62,746.10 | 59,205.13
---|---|---|---|---|---|---
*Isentropic energy capture vs measured output.*

### Table 7. Result of Boiler Exergy and Energy Calculation

| LOSS POINT | Energy Losses (% of Input) | | | | | |
|---|---|---|---|---|---|---|
| | 380MW | 300MW | 250MW | 380MW | 300MW | 250MW |
| Dry Gas | 4.75% | 4.91% | 4.69% | | | |
| Moisture in Coal | 8.85% | 9.18% | 8.75% | | | |
| Moisture in air | 0.32% | 0.33% | 0.31% | | | |
| Unburned Carbon | 0.07% | 0.08% | 0.10% | | | |
| Radiation & Convection | 0.42% | 0.54% | 0.62% | | | |
| Unaccounted | 6.00% | 4.05% | 7.32% | | | |
| Margin of Error | 0.50% | 0.50% | 0.50% | | | |
| Total Losses | 20.92 | 19.58 | 22.29 | | | |
| Efficiency | 79.08% | 80.42% | 77.71% | | | |

### Table 8. Feed Water Heater Energy Loss and Exergy Destruction

| Equipment | Energy Losses (kJ/s) | Exergy Destruction (kJ/s) | | | | |
|---|---|---|---|---|---|---|
| | 380MW | 300MW | 250MW | 380MW | 300MW | 250MW |
| HPH 7 | 27,558.28 | 48,165.76 | 30,227.25 | 30,858.84 | 12,918.41 | 36,832.59 |
| HPH 6 | 12,473.61 | 25,834.01 | 15,075.07 | 15,075.07 | 6,817.72 | 15,103.61 |
| HPH 5 | 41,361.63 | 25,854.19 | 15,573.84 | 40,536.78 | 31,952.36 | |
| Deaerator | 45,350.75 | 8,981.09 | 418.47 | 10,719.76 | 12,569.43 | 44,511.27 |
| LPH 3 | 3,288.45 | 7,340.44 | 9,936.58 | 9,346.51 | 25,953.39 | 30,926.57 |
| LPH 2 | 4,311.75 | 11,295.54 | 8,723.45 | 7,020.53 | 10,405.86 | 14,581.12 |
| LPH 1 | 25,770.93 | 292.69 | 795.52 | 1,672.94 | 24,326.92 | 4,750.70 |
| Condenser | 503,802.22 | 9,114.73 | 12,483.57 | 14,422.05 | 321,973.38 | 211,052.73 |

### Table 9. Efficiency of CFPP

| EFFICIENCY | Energy | Exergy | | | | |
|---|---|---|---|---|---|---|
| | 380MW | 300MW | 250MW | 380MW | 300MW | 250MW |
| Boiler Efficiency | 79.08% | 80.42% | 77.71% | 67.09% | 67.97% | 65.09% |
| Turbine Efficiency | 82.29% | 79.41% | 77.57% | 85.54% | 82.87% | 81.13% |
| CFPP Efficiency | 65.07% | 63.86% | 60.28% | 57.39% | 56.33% | 52.81% |

### 4. Result and Discussion

CFPP efficiency Higher at higher load as shown in table 9 due to increase in main-steam pressure as shown in table 1. This CFPP installed capacity 400 MW load, boiler volume was design based on this capacity.

Energy and exergy losses of each equipment as shown in Figure 2. Exergy analysis gives different result from energy analysis. The highest energy loss was heat reject in condenser which is low grade energy following by losses in turbine, feed water and moisture in fuel. The highest exergy loss was in dry gas loss while biggest exergy destruction was in boiler and gas air heater where irreversibility was associate with coal combustion and heat transfer. Design or process improvement should be focused on combustor rather than condenser as misguided by energy balance.
Sankey diagram of energy and exergy flow of this CFPP at 380 MW generator gross output as shown in Figure 3 and Figure 4. Higher energy losses found in Condenser, while most exergy destruction found in the boiler. The energy in the condenser cannot be utilized due to low temperature and pressure. On the other hand, exergy loss or destruction in Boiler gives more potential for improvement. Therefore, exergy analysis gives more valuable information for action plant in efficiency improvement.
Report of site observation, slag develop in some corners of the boiler and furnace gas exit temperature exceed the standard. These phenomena support the exergy analysis result that most losses in boiler was dry flue gas loss. RCPS based on EPRI best practice should be performed to identify the main cause and possible correction action.

5. Summary
In this paper, sub-critical CFPP was analyzed both energy and exergy method to evaluate major losses and exergy destruction and then find the most potential area to be improve. Some conclusions could be drawn from this study as follow:
1. Energetic efficiency of CFPP at 250MW, 300MW and 380MW load was 60.28%, 63.86%, and 65.07% respectively while exergetic efficiency was 52.81%, 56.33% and 57.39%.
2. Most energy losses occur in condenser and most exergy destruction was dry gas loss in boiler.
3. Result from exergy analysis give better information on area to be improve.

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