



Thermodynamics Analysis of Natural Gas Fuel Based Furnace/Boiler Integrated with Steam Power Plant: A Theoretical Approach

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Abstract

Energy and Environment both is the core for human comfort and global survival now days. Thermodynamic Analysis of Furnace/Boiler coupled with a steam power plant has been carried out in order to evaluate its performance and irreversibility's by using the generalized mathematical formulation. This paper represents a detailed energy study and thermodynamic analysis for the calculation of ideal work of the whole plant while the work lost in Furnace/Boiler coupled with steam power plant. For this purpose an experiment is carried out in a miniature steam power plant using Methane and 30% Air in excess as a fuel of furnace the hot flue gases are used for steam generation which is further used to operate the steam power plant. After collecting useful data and by applying generalized mathematical formulation our results shows that ideal work of whole plant is $(-266.758 \times 10^3 \text{ kW})$ while the work lost in Furnace/Boiler is $(169.387 \times 10^3 \text{ kW})$ so the Furnace/Boiler efficiency is (63.50 %).

Keywords: Steam power plants, thermodynamic analysis, energy analysis, thermal efficiency, ideal work and lost work.

Introduction

Thermodynamic Analysis is a technique which is based upon the 1st and 2nd law of thermodynamics. These laws provide a base in order to comparing different processes and finding irreversibility's in the process¹.

Generally the performance of thermal power plants is evaluated through the energetic performance which is based upon 1st law of thermodynamics however recently the exergetic analysis which is based upon the 2nd law of thermodynamics has been found to be a useful method in the design, evaluation, optimization and improvements of thermal power plants²⁻⁵.

Thermodynamic Analysis is a technique which is based upon the 1st and 2nd law of thermodynamics actually represents a 3rd step in the plant system analysis. The aim of thermodynamic analysis is to identify the magnitude and locations of energy losses in order to improve existing systems or process or to develop new processes by applying mass and energy balances⁶.

This analysis is helpful to quantify efficiency loss in a process due to the loss in energy. Such analysis cannot apparently point out how the process can be improved. However it can signify that where process can be improved and therefore it will signify that which areas should be given consideration sometime the simple energy balance will not sufficient to find out the simple flaws. Is such circumstance exergy analysis is well thought out to be significant to locate the system imperfection⁷⁻¹⁴.

Previous research shows that Furnace/Boiler has largest energy

and exergy losses in a steam power plant these losses in Furnace/Boiler can be reduced by pre-heating the combustion air and reducing the air to fuel ratio also previous research shows that the energy efficiency of the Boiler is 89.21% and the exergy efficiency of a boiler is 45.48%^{15,16}.

Steam power plants are basically the assembly of system where electricity is generated by the interaction of various mechanical and electrical devices. But the core of the steam power plant is a steam generator usually a Furnace/Boiler¹⁷.

Energy and exergy analysis of power plants has increasingly attracted the researcher interest because it is helpful in identifying the imperfections and energy losses and making system efficient^{18,19}.

The performance of a steam power plant based upon rankine cycle can be increased by increasing the boiler pressure, decreasing the condenser pressure or superheating the steam to a very high temperature²⁰.

Several shows that the efficiency of a steam power plant based upon the rankine cycle can be increased by introducing the feed water pre-heating system. This can be also improved by dividing overall enthalpy equally by feed water heaters. It was proposed that the thermal efficiency of steam power plant by decreasing flow rate of steam but late scientist try to improve thermal efficiency by increasing the steam pressure. This factor leads to a problem of steam degradation. This problem is solved by introducing steam re-heating system after the high pressure turbine exhaust which leads to decrease the moisture content in

low pressure turbine exhaust²¹⁻²⁵.

Exergy analysis of a steam power plant reveals that efficiency can be increased by reduction in imperfections in steam generator, reduction in excess air for combustion and reduction in stack gas temperature²⁶.

A combined energy and exergy analysis shows that major losses occur at Furnace/Boilers, super heaters, economizer and air pre-heaters²⁷.

A rankine cycle commonly consist of 4 processes shown in figure-1²⁸.

1-2 Isentropic Expansion (Steam Turbine) 2-3 Isobaric Heat Rejection (Condenser) 3-4 Isentropic Compression (Pump) 4-1 Isobaric Heat Supply (Furnace/Boiler)

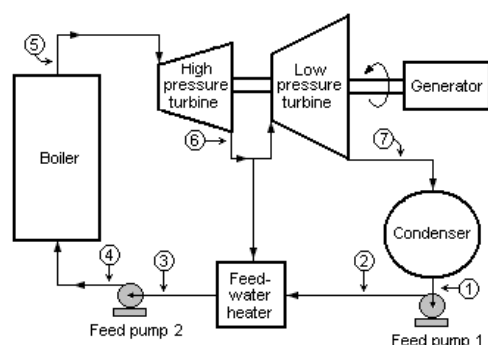
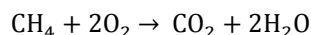


Figure-1
Steam Power Plant

Methodology

In a steam power plant steam undergoes in a cyclic process, the only changes that need be considered for calculation of the ideal work are those of the gases passing through the furnace. The reaction occurring is:



For this reaction occurring at a surface temperature of 298.15K the data table C.4 gives the Entropy S and Enthalpy H:

$$\Delta H_{298}^{\circ} = -393,509 + (2)(-241,818) - (-74,250)$$

$$\Delta H_{298}^{\circ} = -802,625 \text{ J}$$

$$\Delta G_{298}^{\circ} = -394,359 + (2)(-228,572) - (-50,460)$$

$$\Delta G_{298}^{\circ} = -801,043 \text{ J}$$

So

$$\Delta S_{298}^{\circ} = \frac{\Delta H_{298}^{\circ} - \Delta G_{298}^{\circ}}{298.15}$$

$$\Delta S_{298}^{\circ} = \frac{-802,625 - (-801,043)}{298.15}$$

$$\Delta S_{298}^{\circ} = -5.306 \text{ JK}^{-1}$$

On the basis of 1 Mole of methane burned with 30% excess air, the composition of air entering to the furnace can be calculated as:

$$\text{O}_2: (2)(1.3) = 2.6 \text{ mole}$$

$$\text{N}_2: (2.6)\left(\frac{79}{21}\right) = 9.7810 \text{ mole}$$

$$\text{Total} = 12.3810 \text{ mole of air}$$

The composition of hot flue gases which are formed after the complete combustion of methane with 30% excess air can be calculates as:

$$\text{CO}_2: 1 \text{ mole} \quad y_{\text{CO}_2} = 0.0747$$

$$\text{H}_2\text{O}: 2 \text{ mole} \quad y_{\text{H}_2\text{O}} = 0.1495$$

$$\text{O}_2: 0.6 \text{ mole} \quad y_{\text{O}_2} = 0.0448$$

$$\text{N}_2: 9.7810 \text{ mole} \quad y_{\text{N}_2} = 0.7310$$

$$\text{Total: } 13.3810 \text{ mole of flue gases} \quad \sum y_i = 1.00000$$

In the furnace there are 4 steps involved 1st is the entering and un-mixing of air 2nd is the standard reaction at 298.15K 3rd is the formation and mixing of hot flue gases and 4th one is the heating step in order to generate steam. Now we calculate the change in enthalpy and entropy for each individual step by using the mathematical relationships of Property Changes of Mixing as:

Step a: For the un-mixing the entering of air.

$$\Delta H_a = 0$$

$$\Delta S_a = nR \sum y_i \ln y_i \quad (1)$$

$$\Delta S_a = (12.3810)(8.314)(0.21 \ln 0.21 + 0.79 \ln 0.79)$$

$$\Delta S_a = -52.8986 \text{ JK}^{-1}$$

Step b: For standard reaction at surface temperature of 298.15K

$$\Delta H_b = \Delta H_{298}^{\circ} = -802,625 \text{ J}$$

$$\Delta S_b = \Delta S_{298}^{\circ} = -5.306 \text{ JK}^{-1}$$

Step c: For mixing and formation of flue gases.

$$\Delta H_c = 0$$

$$\Delta S_a = nR \sum y_i \ln y_i$$

$$\Delta S_a = (-13.3810)(8.314)(0.0747 \ln 0.0747 + 0.1495 \ln 0.1495 + 0.0448 \ln 0.0448 + 0.7310 \ln 0.7310)$$

$$\Delta S_a = 94.1283 \text{ JK}^{-1}$$

Before going to the step d we will find out the flue gas exit temperature. Previous research shows that the flue gas exit temperature is always higher than the furnace because otherwise heat will not flow from furnace gases to the walls and loads. An empirical relation is developed for the estimation of flue gas exit temperature given below as²⁹.

$$\text{Flue Gas Exit Temperature (F}^{\circ}\text{)} = 740 + (0.758 \times \text{Furnace Temperature}) \quad (2)$$

For a temperature of 100C^o or 212F^o inside the furnace the flue gas exit temperature is given by.

$$\text{Flue Gas Exit Temperature (F}^{\circ}\text{)} = 740 + (0.758 \times 212)$$

$$\text{Flue Gas Exit Temperature (F}^{\circ}\text{)} = 900.6960 \text{ F}^{\circ} = 755.75 \text{ K}$$

Step d: for the heating step the mean heat capacities between the 298.15K and 755.75K are calculated for flue gas components as follows³⁰.

For CO₂:

$$\frac{(C_p)_H}{R} = A + \frac{B}{2}T_o(\tau + 1) + \frac{C}{3}T_o^2(\tau^2 + \tau + 1) + \frac{D}{\tau T_o^2} \quad (3)$$

$$\frac{(C_p)_H}{8.314} = 5.457 + \frac{1.045 \times 10^{-3}}{2} \times 298.15(2.5348 + 1) + 0 + \frac{(-1.157 \times 10^5)}{(2.5348)(298.15)^2}$$

$$(C_p)_H = 45.6730 \text{ Jmole}^{-1} \text{ K}^{-1}$$

$$\frac{(C_p)_S}{R} = A + \left[BT_o + \left(CT_o^2 + \frac{D}{\tau^2 T_o^2} \right) \left(\frac{\tau+1}{2} \right) \right] \left(\frac{\tau-1}{\ln \tau} \right) \quad (4)$$

$$(C_p)_S/8.314 = 5.457 + [1.045 \times 10^{-3} \times 298.15 + (0 + ((-1.157 \times 10^5)/(2.5348)^2 ((298.15)^2))((2.5348 + 1)/2)]((2.5348 - 1)/\ln 2.5348)$$

$$(C_p)_S = 30.5766 \text{ Jmole}^{-1} \text{ K}^{-1}$$

For H₂O:

$$\frac{(C_p)_H}{R} = A + \frac{B}{2}T_o(\tau + 1) + \frac{C}{3}T_o^2(\tau^2 + \tau + 1) + \frac{D}{\tau T_o^2}$$

$$\frac{(C_p)_H}{8.314} = 3.470 + \frac{1.450 \times 10^{-3}}{2} \times 298.15(2.5348 + 1) + 0 + \frac{(0.121 \times 10^5)}{(2.5348)(298.15)^2}$$

$$(C_p)_H = 35.6479 \text{ Jmole}^{-1} \text{ K}^{-1}$$

$$\frac{(C_p)_S}{R} = A + \left[BT_o + \left(CT_o^2 + \frac{D}{\tau^2 T_o^2} \right) \left(\frac{\tau+1}{2} \right) \right] \left(\frac{\tau-1}{\ln \tau} \right)$$

$$\frac{(C_p)_S}{8.314} = 3.470 + [1.450 \times 10^{-3} \times 298.15 + (0 +$$

$$\frac{(0.121 \times 10^5)}{(2.5348)^2 (298.15)^2} \left(\frac{2.5348+1}{2} \right) \left(\frac{2.5348-1}{\ln 2.5348} \right)]$$

$$(C_p)_S = 31.3907 \text{ Jmole}^{-1} \text{ K}^{-1}$$

For N₂:

$$\frac{(C_p)_H}{R} = A + \frac{B}{2}T_o(\tau + 1) + \frac{C}{3}T_o^2(\tau^2 + \tau + 1) + \frac{D}{\tau T_o^2}$$

$$(C_p)_H/8.314 = 3.280 + (0.593 \times 10^{-3})/2 \times 298.15(2.5348 + 1) + 0 + ((0.04 \times 10^5)/((2.5348)((298.15)^2)))$$

$$(C_p)_H = 30.0119 \text{ Jmole}^{-1} \text{ K}^{-1}$$

$$\frac{(C_p)_S}{R} = A + \left[BT_o + \left(CT_o^2 + \frac{D}{\tau^2 T_o^2} \right) \left(\frac{\tau+1}{2} \right) \right] \left(\frac{\tau-1}{\ln \tau} \right)$$

$$\frac{(C_p)_S}{8.314} = 3.280 + [0.593 \times 10^{-3} \times 298.15 +$$

$$\left(0 + \frac{(0.04 \times 10^5)}{(2.5348)^2 (298.15)^2} \right) \left(\frac{2.5348+1}{2} \right) \left(\frac{2.5348-1}{\ln 2.5348} \right)]$$

$$(C_p)_S = 28.2892 \text{ Jmole}^{-1} \text{ K}^{-1}$$

For O₂:

$$\frac{(C_p)_H}{R} = A + \frac{B}{2}T_o(\tau + 1) + \frac{C}{3}T_o^2(\tau^2 + \tau + 1) + \frac{D}{\tau T_o^2}$$

$$\frac{(C_p)_H}{8.314} = 3.639 + \frac{0.506 \times 10^{-3}}{2} \times 298.15(2.5348 + 1) + 0 + \frac{(-0.227 \times 10^5)}{(2.5348)(298.15)^2}$$

$$(C_p)_H = 31.6290 \text{ Jmole}^{-1} \text{ K}^{-1}$$

$$\frac{(C_p)_S}{R} = A + \left[BT_o + \left(CT_o^2 + \frac{D}{\tau^2 T_o^2} \right) \left(\frac{\tau+1}{2} \right) \right] \left(\frac{\tau-1}{\ln \tau} \right)$$

$$\frac{(C_p)_S}{8.314} = 3.639 + [0.506 \times 10^{-3} \times 298.15 +$$

$$\left(0 + \frac{(-0.227 \times 10^5)}{(2.5348)^2 (298.15)^2} \right) \left(\frac{2.5348+1}{2} \right) \left(\frac{2.5348-1}{\ln 2.5348} \right)]$$

$$(C_p)_S = 30.6866 \text{ Jmole}^{-1} \text{ K}^{-1}$$

Finally the results of mean heat capacities are summarized in table-1.

Table-1
Mean Heat Capacities of Flue gas Components

Components	$(C_p)_H$	$(C_p)_S$
Units →	$\text{Jmole}^{-1} \text{ K}^{-1}$	$\text{Jmole}^{-1} \text{ K}^{-1}$
CO ₂	45.6730	30.5766
H ₂ O	35.6479	31.3907
N ₂	30.0119	28.2892
O ₂	31.6290	30.6866

Each individual heat capacity is multiplied by the number of moles of that species in the flue gas and the products are summarized over all species.

$$(C_p)_H^{total} = 429.4926 \text{ Jmole}^{-1} \text{ K}^{-1}$$

$$(C_p)_S^{total} = 388.4667 \text{ Jmole}^{-1} \text{ K}^{-1}$$

Also

$$\Delta H_d = (C_p)_H^{total} (T - T_o) \quad (5)$$

$$\Delta H_d = 429.4926(755.75 - 298.15)$$

$$\Delta H_d = 196535.8138J$$

$$\Delta S_d = (C_p)_s^{total} \ln\left(\frac{T}{T_o}\right) \quad (6)$$

$$\Delta S_s = 388.4667 \ln\left(\frac{755.75}{298.15}\right)$$

$$\Delta S_s = 361.3183 JK^{-1}$$

For the total process with the basis of methane 1 mole the total enthalpy and entropy can be calculated as.

$$\Delta H = \sum \Delta H_i \quad (7)$$

$$\Delta H = 0 - 802625 + 0 + 196535.8138$$

$$\Delta H = -606.089 kJ$$

$$\Delta S = \sum \Delta S_i \quad (8)$$

$$\Delta S = -52.8986 - 5.306 + 94.1283 + 361.3183$$

$$\Delta S = 0.397 kJ K^{-1}$$

Steam enters in the turbine with a pressure of 8500kPa and 500°C with a flow rate of 70kg/sec. so energy balance can be written as.

$$(70)(3391.6 - 203.4) + n^{o}_{CH_4}(-606.089) = 0 \quad (9)$$

$$n^{o}_{CH_4} = 368.2189 \text{ mole sec}^{-1}$$

Now ideal work of the whole steam power plant can be calculated as.

$$W_{ideal} = n^{o}_{CH_4}(\Delta H - T_o \Delta S) \quad (10)$$

$$W_{ideal} = 368.2189(-606.089 - 298.15 \times 0.397)$$

$$W_{ideal} = -266.758 \times 10^3 kJ$$

In order to calculate the work loss in the furnace first of all we calculate the entropy in the system (furnace/boiler).

$$S_G = n^{o}_{CH_4}(\Delta S) + \text{Steam Flow Rate}(6.6858 - 0.6580) \quad (11)$$

$$S_G = 568.1293 kJ K^{-1}$$

Now work lost in the furnace is given by.

$$W_{lost} = T_o \Delta S \quad (12)$$

$$W_{lost} = 298.15 \times 568.1293$$

$$W_{lost} = 169.387 \times 10^3 kJ$$

This is the work lost only in the furnace/boiler integrated with the steam power plant. The efficiency of the furnace can be calculated as.

$$\text{Efficiency} = \frac{W_{lost}}{W_{ideal}} \quad (13)$$

$$\text{Efficiency} = \frac{169.387 \times 10^3}{266.758 \times 10^3}$$

$$\text{Efficiency} = 63.50\%$$

Results and Discussion

The results of this Theoretical thermodynamic analysis of furnace/boiler integrated with a steam power plant shows that at 1mole of methane with complete combustion in 30% excess air shows an efficiency of 63.50% and the total ideal work of the plant is $-266.758 \times 10^3 kJ$ with a work lost in the furnace is $169.387 \times 10^3 kJ$.

Conclusion

It is concluded that the major source of irreversibility, inefficiency in the steam power plant is furnace/boiler. Because the combustion processes itself accounts for a most of the

entropy generation in the steam power plant unit. So we can improve the furnace efficiency by updating the thermostat, furnace inspection once in one year. We also prevent the heat loss by providing the insulate jacket around the furnace.

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