EFFECT OF VARIOUS FUELS ON EXERGY ANALYSIS OF HRSG OF COMBINED CYCLE POWER PLANT

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Abstract: Most of the power plants are designed on the basis of energetic performance which is further based on first law of thermodynamics. However, this strategy is unable to account for the real useful energy loss as it unable to differentiate between the quality and quantity of energy. Therefore, the present work is an attempt to analyse the exergy of the HRSG of combined cycle power plant and to determine major losses of available energy the exergy efficiency by using various in the combustion chamber of gas turbine of combined cycle power plant.

1. INTRODUCTION

In power industry, various fuels are utilized in gas turbine power plant based upon several possible scenarios i.e. availability and costs. Every fuel which is employed to burn and generate the heat, comes with some constraints attached with its utilization. Though, constraints may be related to its byproducts (to be analyzed during greenhouse effect observations) or power production cost (to analyze the efficiency of power plant). In later point of view, the energetic and exergetic analysis are the way to analyze the efficiency of a particular components or overall plant. In this paper, various fuels are taken for the observation in combined cycle power plant to acknowledge the energy and exergetic efficiency. The concerned fuels in present work are compressed natural gas commonly known as CNG, Naphtha and Light Diesel oil (LDO).

CNG

CNG is mainly composed of Methane(CH_4), produces lesser undesirable byproducts than the other conventional fuels. CNG is compressed form of natural gas when it is compressed to its 1% of the volume. This fuel is more often used in combustion chamber for gas turbine power generation. CNG, unlike gasoline and diesel does not depend on the crude oil prices. Source of production is definitely petroleum based but the way it is extracted or produced is quite different. In India, Natural gas fields exist in Assam, Gujarat, Krishna Godavari basin and Cauvery basin. Different gas extraction fields quote different prices because the pricing dominantly depends on the way it is extracted from the natural gas fields.

Naphtha

Naphtha is an intermediate hydrocarbon mixture distillated from crude oil and natural gas condensates. It is considered a component between gasoline and kerosene. So, the availability and pricing of Naphtha is quite correlated with that of Crude oil. Naphtha refers to a mixture of Hydrocarbons which is a flammable liquid. It is made of paraffin, napthene i.e. cyclic paraffins and aromatic hydrocarbons ranging from 5 carbon atoms to 12 carbon atoms. The initial boiling point(IBP) and final boiling point (FBP) are 35 ^{0}C and 200 ^{0}C respectively. It is categorized into two types because the distillation occurs in different stream. These are Light Naphtha and Heavy Naphtha. Light Naphtha contains its major parts of hydrocarbons with 5 to 6 carbons having IBP and FBP of 30 ^{0}C and 145 ^{0}C respectively, while Heavy Naphthacomprises of hydrocarbons with 7 to 12 carbons having IBP and FBP of 140 ^{0}C and 205 ^{0}C respectively.

LDO

Light Diesel oil is liquid fuel for stationary gas turbine used in power generating stations. It comes with advantage of good storage and combustion properties. LDO is byproduct of crude oil distillation process while temperature maintained between 200 ^{0}C and 350 ^{0}C. It comprises of its 3/4thpart of aliphatic hydrocarbons ($C_{10}H_{20}$-$C_{15}H_{28}$) and 1/4th part of aromatic hydrocarbons i.e. Benzene, Styrene. LDO has flash point of approximately 55 ^{0}C. This fuel is considered suitably great for atomization and combustion. That's why most of Gas turbines are well capable to handle this fuel without any significant modification. Minor concerns about emissions and thermal loading have to be taken care of.

2. EXERGETIC EVALUATION

Exergy is known as maximum available work obtained from a system when system is brought to dead state (state of environment) from a particular state while interacting only with environment. It will not be sufficient to elaborate without mentioning the reference environment state. Exergy analysis makes more sense as it takes conservation of mass, conservation of energy along with second law of thermodynamics while energy analysis takes only first law of thermodynamics, which is not sufficient to determine the true magnitude of losses and their locations. Hence, to improvise a system (here, refer to combined cycle power plant), exergetic evaluation is a technique one must rely on.

Total Exergy of a system is defined as exergy obtained from Heat and work processes. Though, the process comprises both the heat and work transfer are common in formulation of any power plant problem. Here on, it can be written as

$$\Delta\dot{E}_{system} = \Delta\dot{E}_{heat} - \Delta\dot{E}_{work} \quad (2.1)$$

$\Delta\dot{E}_{heat}$: It is the exergy (rate) linked with heat transfer rate $\dot{Q}$, presumption of uniform temperature distribution in thermal energy reservoir. It is given by:

$$\Delta\dot{E}_{heat} = \left(1 - \frac{T_0}{T}\right)\dot{Q} \quad (2.2)$$

$\Delta\dot{E}_{work}$: Work, itself is measure of available energy i.e. exergy is every aspect.So exergy transfer can be written as work transfer to which it corresponds

$$\Delta\dot{E}_{work} = W + \int P_0 dV \quad (2.3)$$

Putting equations (2) and (3) in equation (1):

$$\Delta\dot{E}_{system} = \left(1 - \frac{T_0}{T}\right)\dot{Q} - (W + \int P_0 dV) \quad (2.4)$$

$$\Delta\dot{E}_{system} = \left(\dot{Q} - T_0 \int dS\right) - (W - \int P_0 dV) \quad (2.5)$$

According to first law of thermodynamics:

$$\Delta E = Q - W \quad (2.6)$$

After eliminating Q and W, equations (5) yields to:

$$\Delta\dot{E}_{system} = \Delta E - T_0 \int dS + \int P_0 dV \quad (2.7)$$

Expanding it by considering macro form of energies:

$$\Delta\dot{E}_{system} = \Delta U - T_0 \int dS + \int P_0 dV + \mathrm{m}\frac{1}{2}v^2 + \mathrm{mgz} \quad (2.8)$$

Integrating above equation between the state point and dead state:

$$\dot{E} = U - U_0 - T_0(S - S_0) + P_0(V - V_0) + m\frac{1}{2}v^2 + mgz \quad (2.9)$$

The total exergy of system comprises of its 4 components known as:

1. Kinetic Exergy: It is the exergy of a system due to its velocity with respect to a reference point of environment. It is same as kinetic energy.
2. Potential Exergy: Potential exergy is associated with potential energy which is determined with respect to datum level of the environment. It must also include force generated by the pressure effects of environment components.
3. Physical Exergy: Physical exergy is a part of total exergy due its temperature and pressure points of both state of the system and environment.
4. Chemical exergy: Part of exergy due its chemical composition i.e. mixture of various substances and it is brought to dead state from environment state by involving exchange of substances only with environment.

3. MATHEMATICAL MODELLING

Here, the system taken into consideration is combined cycle power plant which consists of compressor, combustor and gas turbine, heat recovery steam generator, steam turbine, condenser and pump as its main components. The component wise evaluation gives more appropriate data about losses and their location so that system can be improved significantly.

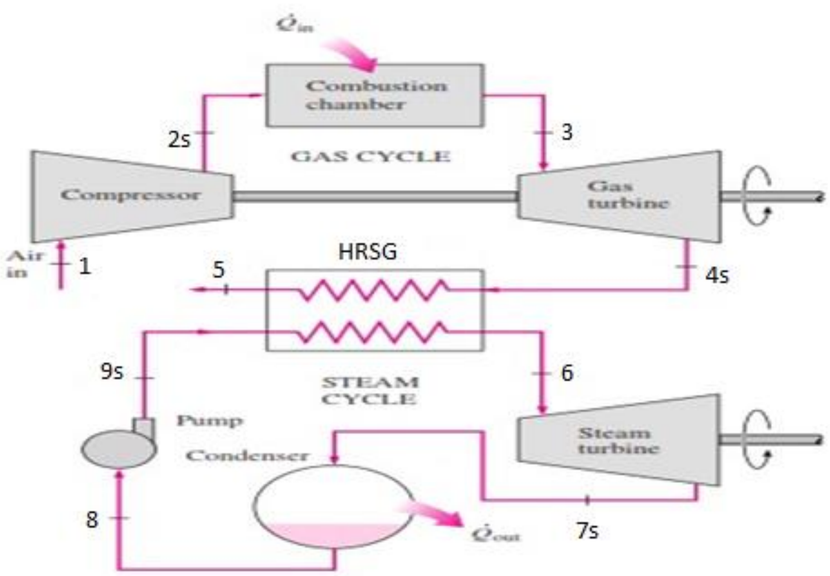

Figure 1: Schematic representation of Combined Cycle Power Plant

Topping cycle (Gas Turbine) work on the concept of Brayton cycle. Here, unlike ideal conditions, in this consideration the isentropic efficiency of compressor and gas turbine taken as 85% and combustion chamber efficiency is taken as 90%. The bottoming cycle works on standard Rankine cycle. Thefollowing T-S (Temperature- Entropy) diagram shows the various processes and state points of components.

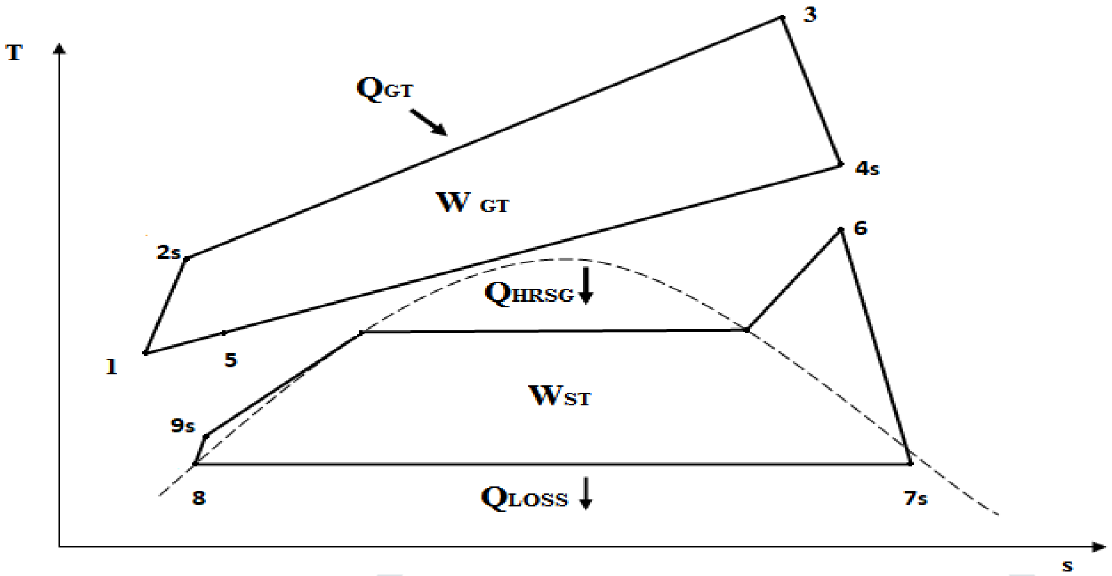

Figure 2: T-S diagram of Combined cycle power plant with ideal and actual states.

The following formulation is taken as base for analysis of gas turbine power plant:

i. Compressor

$$X_1 + W_c = X_{2s} + \Delta X_{dest.} \quad (3.1)$$

$$\Delta X_{dest.} = X_1 + W_c - X_{2s} \quad (3.2)$$

$$\eta_{exer.} = \frac{X_{2s} - X_1}{W_c} \quad (3.3)$$

Where,

$$X_1 = \dot{m}_a [h_1 - h_0 - T_0(s_1 - s_0)] \quad (3.4)$$

$$X_2 = \dot{m}_a [h_{2s} - h_0 - T_0(s_{2s} - s_0)] \quad (3.5)$$

ii. Combustion Chamber

$$X_{2s} + X_f = X_3 + X_{cc} \quad (3.6)$$

$$X_f = X_{ph} + X_{ch} \quad (3.7)$$

$$X_{ph} = \dot{m}_a [h_f - h_0 - T_0(s_f - s_0)] \quad (3.8)$$

$$X_{ch} = \dot{m}_f e_{ch} \quad (3.9)$$

For fuel with composition C_xH_y, the value of Ω is determined from following expression,

$$\Omega = 1.033 + 0.0169 \frac{y}{x} - \frac{0.0698}{X} \quad (3.10)$$

For CNG, the main component is Methane (CH_4) so X=1, Y=4,
then, $\Omega = 1.06$

$$X_f = \dot{m}_f (1.06 * LCV) \quad (3.11)$$

LCV: It is known as Lower calorific value; Lower calorific value means the total quantity of heat liberated from combustion of unit mass or unit volume of given fuel when side products are allowed to escape. Fuels taken into consideration are CNG, Naphtha and Light diesel oil (LDO) having the LCV of 43500 kJ/kg, 44900 kJ/kg and 42680 kJ/kg respectively.

$$\Delta X_{dest.} = X_{2s} + X_f - X_3 \quad (3.12)$$

$$\eta_{exer.} = \frac{X_3}{X_{2s} + X_f} \quad (3.13)$$

iii. Gas Turbine

$$\Delta X_{dest.} = X_3 - X_{4s} - X_T \quad (3.14)$$

$$\eta_{exer.} = \frac{W_{GT}}{X_3 - X_{4s}} \quad (3.15)$$

iv. HRSG

$$\Delta X_{dest.} = X_{in} - X_{out} \quad (3.16)$$

Where,

$$X_{4s} = (\dot{m}_a + \dot{m}_f)\psi_{4s} \quad (3.17)$$

$$X_{9s} = \dot{m}_w\psi_{9s} \quad (3.18)$$

$$X_{in} = X_{4s} + X_{9s} \quad (3.19)$$

$$X_5 = (\dot{m}_a + \dot{m}_f)\,\psi_5 \quad (3.20)$$

$$X_6 = \dot{m}_w\psi_6 \quad (3.21)$$

$$X_{out} = X_5 + X_6 \quad (3.22)$$

$$\eta_{II} = \frac{X_{9s} - X_6}{X_{4s} - X_5} \quad (3.23)$$

$$(X_{4s} - X_5) = (\dot{m}_a + \dot{m}_f)\,[(h_{4s} - h_5) - T_0(s_{4s} - s_5)] \quad (3.24)$$

$$(X_{9s} - X_6) = (\dot{m}_w)\,[(h_{9s} - h_6) - T_0(s_{9s} - s_6)] \quad (3.25)$$

4. RESULTS AND DISCUSSION

To analyze the nature of each fuel on various components in operation, fuels are added in combustion chamber to burn with air and generate heat. Fuel comes to combustion chamber at the unit mass flow rate (in kg/s). To fluctuate Air fuel ratio (AFR), the mass flow rate (in kg/s) of air is varied from intake through compressor. So the change in performance of compressor because of variation in AFR is evident but fuel is added in combustion chamber so there will be no effect of various fuels on the performance of compressor. The components after compressor have been analyzed over results. Hence forth, exergetic analysis outcomes of HRSG are shown in figures.

HRSG Results

Figure. 3, 4 and 5 show the exergetic efficiency of HRSG as a function of pressure ratio. The pressure ratio is being varied from 4 to 24 in the step of 4. Curves have been obtained on various Air Fuel Ratios as shown in figure. Exergetic efficiency is maximum at AFR 90 and minimum at AFR 50. At lower pressure ratio, the exit temperature from gas turbine is low so corresponding available energy is low while the stream entering into HRSG. With the gradual increase in pressure ratio, exergetic efficiency is increasing. Efficiency increases as the AFR increases, because it contains more air to flow through the heat exchanger which is capable to transfer more energy. LDO as fuel results highest Exergetic Efficiency of HRSG in higher AFR range.

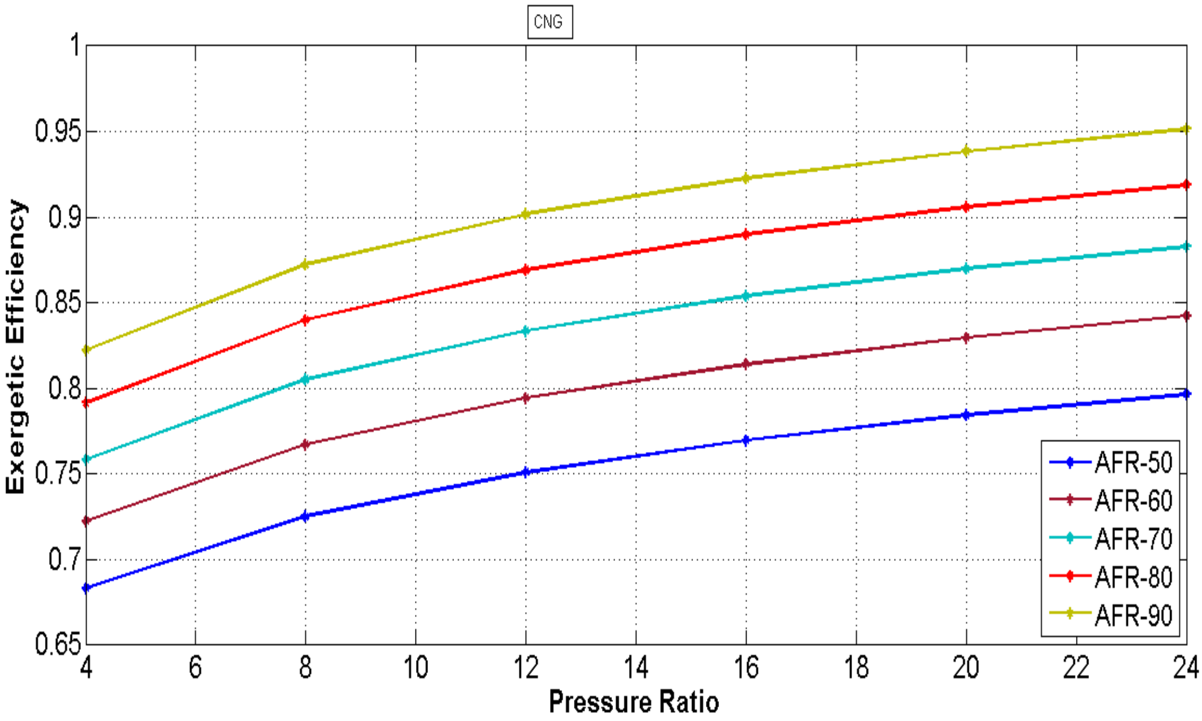

Figure 3: Variation of Exergetic efficiency of HRSG on CNG Fuel vs. Pressure ratio

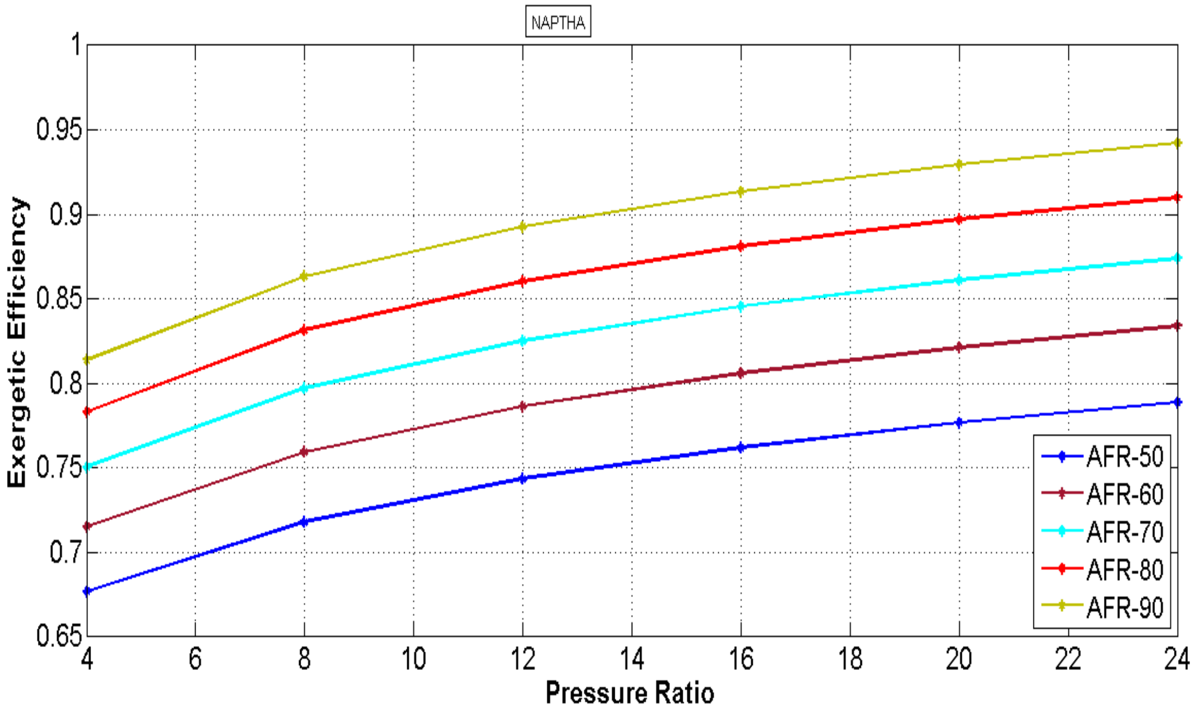

Figure 4: Variation of Exergetic efficiency of HRSG on NAPTHA Fuel vs. Pressure ratio

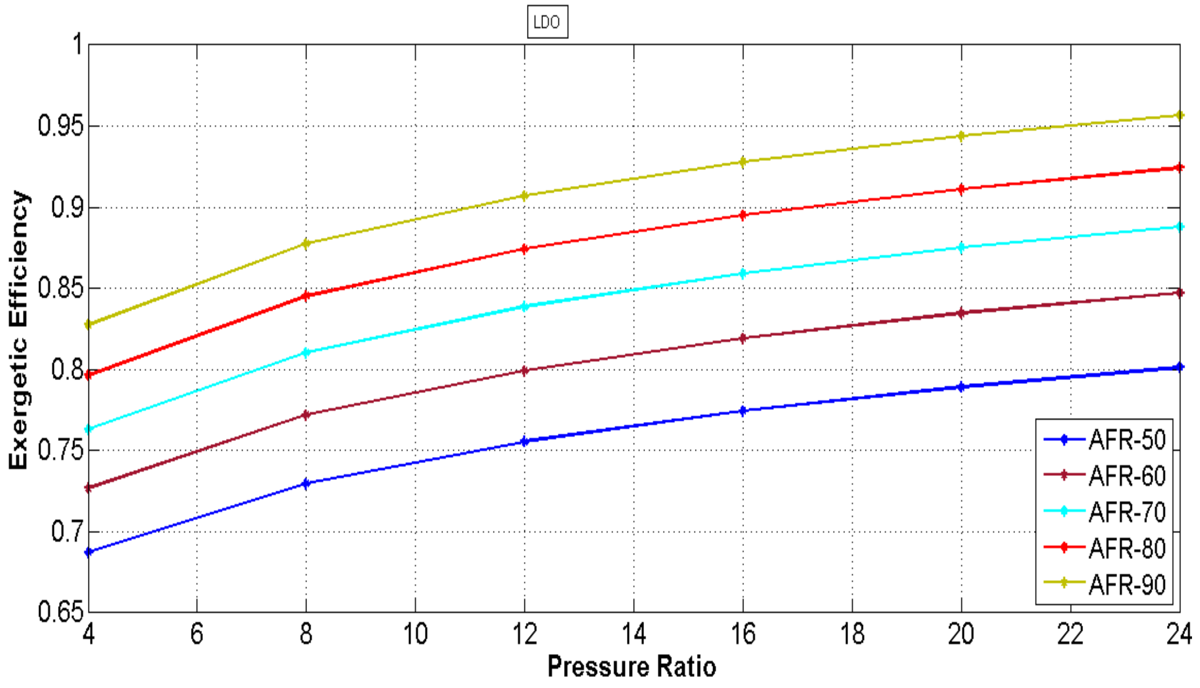

Figure 5: Variation of Exergetic efficiency of HRSG on LDO Fuel vs. Pressure ratio

5. CONCLUSION

The exergy evaluation of Gas turbine power plant was carried out to distinguish the location and amount of losses in entire system. All three fuels have shown different characteristics on different components of combined cycle power plant. The deciding parameter is taken as exergetic efficiency of each component while changing the fuel while observations have been made over a range of pressure ratios.

In HRSG highest exergetic efficiency is the LDO fuel which is attaining the while that of NAPTHA is lowest.

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