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Thermodynamic Analysis of GT Cycle with Naphtha or Natural Gas as the Fuel: A Thermodynamic Comparison

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***Abstract*—**In this paper, a comparative study is done between two fuels, naphtha and natural gas (NG), for a gas turbine (GT) plant of 32.5 MW with the same thermodynamic configuration. From the energy analysis, it is confirmed that the turbine inlet temperature (TIT) of the gas turbine in the case of natural gas is higher as compared to naphtha, and hence the isentropic efficiency of the turbine is better. The result from the exergy analysis also confirms that due to high turbine inlet temperature in the case of natural gas, exergy destruction in combustion chamber is less. But comparing two fuels for overall analysis, naphtha has higher energy and exergetic efficiency as compared to natural gas.

***Keywords*—**Exergy, gas turbine, naphtha, natural gas.

I. Introduction

ENERGY is the cornerstone of life [1]. It is an indicator showing development of countries and living standards of communities. However, inefficient use of energy has resulted in environmental degradation which has increased extreme weather events and led the researcher to improve the performance of the energy system instead of searching a new one.

Generally, the performance of a power plant is evaluated using first law of thermodynamics which does not give the true potential of the energy system. Hence, to evaluate the true potential of an energy system, exergy analysis [2] has been adopted as a useful method in the improvement of energy systems such as the gas turbine power plant. Exergy analysis does not only determine magnitude, location and cause of irreversibility, but also provides meaningful assessment of individual component efficiency [3]. Also, exergy analysis explains how fuel exergy is used and destroyed in the energy conversion process that takes place in these plants. In the present paper, a GT plant (technical specifications are found in Table I) of 32.5 MW has been taken up for case study. Most of the past studies of energy and exergy of a GT plant are performed on natural gas, and few have focused on some other alternative like naphtha, high speed diesel, etc. The present paper presents a comparison between energy and exergy analysis of a GT plant based on naphtha and natural gas. The lower heating value (LHV) of naphtha is being provided by supplier and the LHV of natural gas has been taken up [4].

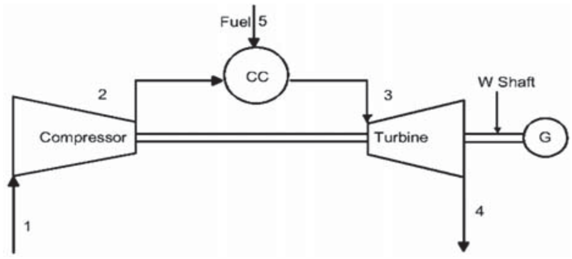

Fig. 1 Open cycle gas turbine

TABLE I
Technical Specification of GT1

PARAMETERS	GT1 (Naphtha)	GT1 (NG)
Mass flow rate	110.2 kg/sec	110.2 kg/sec
Compressor Pressure	8.9 bar	8.9 bar
Compressor Temperature	366°C	366°C
Fuel	2.57 kg/sec, 15.2 bar, 34°C	2.57 kg/sec, 15.2 bar, 34°C
Rated work	32.5 MW	32.5 MW
Actual work	24.45 MW	24.45MW
LHV	44079 kJ/kg	48806 kJ/kg

II. Modelling of Proposed System

Some simplified assumptions are listed below for modelling purposes [2]:

- Steady-state operation of system is assumed, neglecting potential and kinetic energy.
- Fuel has been modelled as naphtha with the following composition:- $y_{H_2} = 0.1583$, $y_C = 0.8392$, $y_S = 0.001$ and the composition of natural gas is taken up [5].

A. Energy Analysis

The principle of mass conservation, energy conservation with possible interaction as heat and work is presented in the following. The fundamental equations governing energy conservation for a control volume are given as:

(a) Compressor: The energy balance equation for air compressor is given by:

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$$\dot{W}_{AC} = \dot{m}_a c_{pa}(T_2 - T_1) \quad (1)$$

$$\left(\frac{T_{2s}}{T_1}\right) = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{y}} \quad (2)$$

$$\left(\frac{T_{2s}}{T_1}\right) = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{y}} \quad (3)$$

where, T_2 and T_1 indicate temperature of fluid at the outlet and inlet of the air compressor.

(b) Combustion chamber: The energy balance for combustion chamber sub system is given by:

$$\dot{m}_a h_2 + \dot{m}_f \text{LHV} = \dot{m}_g h_3 \quad (4)$$

Specific heat of flue gas varies for naphtha with temperature according to the relation derived in Appendix.

$$c_{p,g}(T)=0.9840+0.0001262T+0.000000146T^2 \quad (5)$$

Similarly, the specific heat of flue gas varies for natural gas.

$$c_{p,g}(T)=0.991615+0.0000699703T \quad (6)$$

(c) Gas turbine: The energy balance equation for gas turbine is given by:

$$\dot{W}_{GT} = \dot{m}_g(h_3 - h_4) \quad (7)$$

The first law efficiency of gas turbine is given by:

$$\eta_{GT} = \frac{T_3 - T_4}{T_3 - T_{4s}} \quad (8)$$

Here, $\dot{m}_g$ stands for the mass flow rate of flue gas, which is calculated as:

$$\dot{m}_g = \dot{m}_f + \dot{m}_a \quad (9)$$

The net power can be expressed as:

$$\dot{W}_{net} = \dot{W}_{GT} - \dot{W}_{AC} \quad (10)$$

where, T_3 and T_4 indicate the temperature of gas at the inlet and outlet of the gas turbine, respectively. η_{GT} is isentropic efficiency of the gas turbine.

B. Exergy Analysis

Exergy is the maximum useful work obtained from a system, and it is a widely accepted tool for the thermodynamic analysis of a system. The governing equation for exergy analysis is given as:

$$\dot{E}_{x,heat} + \sum_i \dot{m}_i e_{x,i} = \sum_e \dot{m}_e e_{x,e} + \dot{E}_{x,w} + \dot{I}_{dest} \quad (11)$$

$$\dot{E}_{x,heat} = (1 - \frac{T_0}{T_i}) \times \dot{Q}_i \quad (12)$$

$$\dot{E}_W = \dot{W} \quad (13)$$

$$E_x = E_{x,\text{physical}} + E_{x,\text{chemical}} \quad (14)$$

In (12), $\dot{E}_{x,heat}$ is the exergy flow generated due to heat transfer. Similarly, (13) shows the exergy flow generated due to work.

In order to calculate physical exergy of water/steam phases, the equation written below is used.

$$e_{x,physical} = (h - h_0) - T_0(s - s_0) \quad (15)$$

where, h_0 and s_0 stand for enthalpy and entropy values of environment at dead-state, respectively. In the thermodynamic analysis, the chemical exergy of fuel and combustion products have important role. The chemical exergy of naphtha is determined by (16).

$$\zeta = \frac{e_{x,fuel}}{\text{LHV}} \quad (16)$$

where, ζ represents the ratio of chemical exergy to LHV of fuel. For natural gas, the value of ζ is taken as 1.06 [2]. In order to calculate chemical exergy of gaseous fuel and combustion products, the equation written below is used.

$$e_{x,chemical,mixture} = \left[\sum_{i=1}^{n} x_i e_{x,chemical,i} + RT_0 \sum_{i=1}^{n} x_i \ln(x_i)\right] \quad (17)$$

TABLE II
FLUE GAS COMPOSITION IN GT1 FOR NAPHTHA FUEL

Component	Mass fraction	$e_{x,che}$
CO_2	0.07049	442.73
N_2	0.7501	25.71
O_2	0.147	124.06
SO_2	0.00004596	4896.87
H_2O	0.0322	527.77

To calculate the chemical exergy of combustion products, it is keen to know that molar composition after the combustion process. The molar fraction of combustion gases (Tables II and III) produced in GT1 is found by the chemical equation given in Appendix [2] with excess air supply.

TABLE III
FLUE GAS COMPOSITION IN GT1 FOR NATURAL FUEL

Component	Mass fraction	$e_{x,che}$
CO_2	0.04080	442.73
N_2	0.749	25.71
O_2	0.118	124.06
SO_2	0.00004596	4896.87
H_2O	0.1525	527.77

C. Overall Efficiency

Overall energy and exergy efficiency of a GT plant is calculated with the following equation:

$$\eta_{x,\text{overall}} = \frac{\dot{W}_{net,GT}}{\dot{E}_{x,f}} \tag{18}$$

$$\eta_{\text{overall}} = \frac{\dot{W}_{net,GT}}{\dot{m}_{fuel} LHV} \tag{19}$$

Overall exergy efficiency of a GT plant is represented by (18), while the energy efficiency is represented by (19).

II. RESULTS & DISCUSSION

This section presents energy and exergy analysis of GT plant working on naphtha and natural gas with the same configuration.

A. Energy Analysis

Figs. 2 and 3 presents the Sankey diagram [6] of a GT plant with naphtha and natural gas as fuel. From the two diagrams it can be inferred that the temperature of waste heat from natural gas is higher as compared to naphtha. The other results such as isentropic efficiency and inlet and outlet temperature of gas turbine are presented in Table IV.

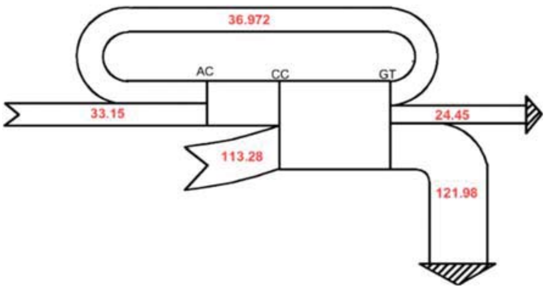

Fig. 2 Sankey diagram of GT power plant with Naphtha as fuel

From Table IV, it can be inferred that turbine inlet temperature (TIT) of natural gas is higher as compared to naphtha, which improves the isentropic efficiency of the gas turbine due to its high TIT. But comparing overall first law efficiency, naphtha has a more promising nature as compared to natural gas due to lower LHV. This shows that natural gas may be good for a component, but naphtha is favorable where efficiency is concerned.

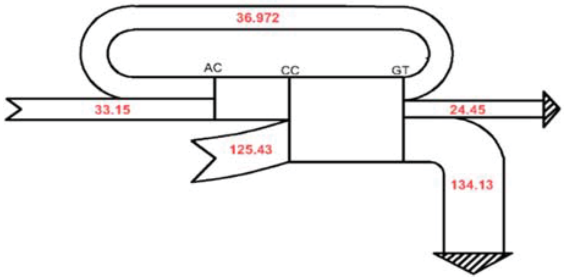

Fig. 2 Sankey diagram of GT power plant with Natural gas as fuel

TABLE IV
THERMODYNAMIC PROPERTY COMPARISON BETWEEN TWO FUELS

Thermodynamic property	**Naphtha**	**Natural gas**
Isentropic efficiency AC	78.85 %	78.85 %
Isentropic efficiency GT	81.5 %	74%
Turbine inlet temperature	1183.6 K	1196.5 K
Turbine outlet temperature	898.5 K	930.2 K
First law efficiency	21.58%	20.18%

B. Exergy Analysis

Tables V and VI present the exergy destruction of a GT power plant with naphtha and natural gas as fuel, presented by the Grassman diagram in Figs. 4 and 5. The percentage of exergy destruction in the compressor is the same in both cases; however, the exergy destruction of the combustion chamber in the case of naphtha is high in contrast to natural gas due to low TIT. Figs. 6 and 7 inspect the comparison of energy and exergy efficiency of GT with naphtha and natural gas. In both cases, the trend is the same i.e. exergy efficiency is less as compared to energy efficiency.

III. CONCLUSIONS

A thermodynamic analysis is performed for a 32.5 MW GT plant and according to first law analysis, the results show the efficiency from natural gas (Energy 19% and Exergy 18%) compared to that of naphtha (Energy 21.5% and Exergy 20. 17%). The reason for the greater efficiency in the case of naphtha is because of the lower heating value as compared to natural gas. Further, from the energy analysis, it can be inferred that due to high LHV in the case of natural gas, the turbine inlet temperature is high which has important role in the combustion chamber. But due to the high turbine inlet temperature in the case on natural gas, the exergy destruction is less than that for naphtha.

TABLE V
COMPARISON OF EXERGY DESTRUCTION & EXERGY EFFICIENCY OF GT PLANT (NAPHTHA)

Equipment	**Exergy destruction rate (kW)**	**Exergy efficiency (%)**
AC	4300	88.3
CC	75410	51.10
GT	6320	90.6

TABLE VI
COMPARISON OF EXERGY DESTRUCTION & EXERGY EFFICIENCY OF GT PLANT (NATURAL GAS)

Equipment	Exergy destruction rate (kW)	Exergy efficiency (%)
AC	4300	88.45
CC	69597.48	58.30
GT	5821.53	90.57

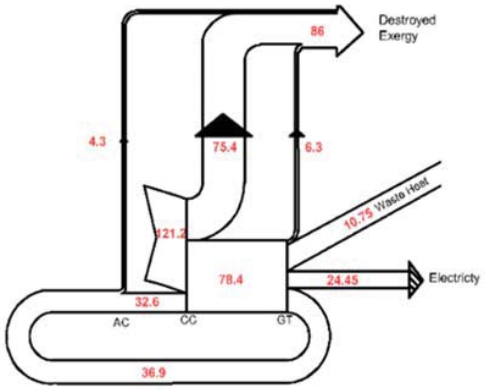

Fig. 4 Grassman diagram of GT power plant with Naphtha as fuel

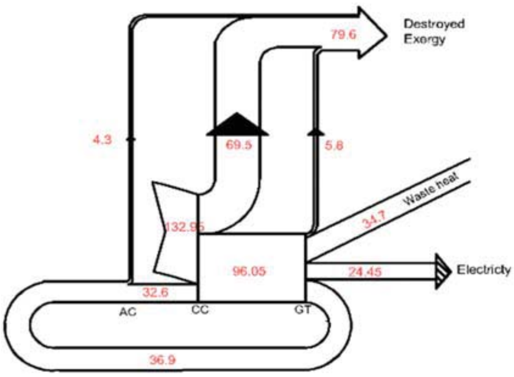

Fig. 5 Grassman diagram of GT power plant with Natural gas as fuel

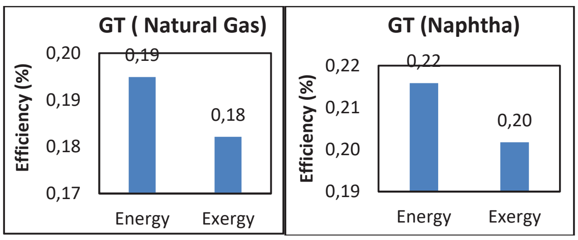

Fig. 6 Comparison of energy efficiency and exergy efficiency of Natural gas & Naphtha

APPENDIX

Flue gas analysis of GT1 with naphtha as fuel

TABLE VII
MOLAR PERCENTAGE OF DIFFERENT COMPONENTS OF NAPHTHA

Composition	Value	Moles
H_2	15.83 %	0.2034
C	83.92 %	0.1796
S	0.1 %	0.00008031
Ash	1.5 %	--------------

$$0.2034H_2 + 0.1796C + 0.00008031S + 0.28(O_2 + 3.78N_2) \rightarrow$$
$$0.179CO_2 + 0.20H_2O + 0.00008031SO_2 + 1.04N_2$$

$$W_T = \frac{0.28}{0.232} \times 32 = 38.62$$

$$\textbf{Excess air} = \frac{W_{actual} - W_{theo}}{W_{theo}} = \mathbf{183\%}$$

$$0.2034H_2 + 0.1796C + 0.00008031S + 0.7924(O_2 + 3.78N_2) \rightarrow$$
$$0.179CO_2 + 0.20H_2O + 0.00008031SO_2 + 2.99N_2 + 0.513O_2$$

TABLE VIII
MOLAR PERCENTAGE OF DIFFERENT COMPONENTS AFTER REACTION

Products of combustion	Moles * Molecular Weight	
CO_2	0.179*44	7.867
H_2O	0.20*18	3.6
SO_2	0.00008013*64	0.00513
N_2	2.99*28	83.72
O_2	0.513*32	16.416
		111.60 kg

Mass of reactant = Mass of product= 111.60 kg

TABLE IX
SPECIFIC HEAT OF VARIOUS GASES (KJ/KMOL K)

Substance	a	b	c
CO_2	22.26	0.05981	-0.00003501
H_2O	32.24	0.01923	0.00001055
SO_2	25.78	0.05715	-0.00003812
N_2	28.90	-0.01571	0.00008081
O_2	25.48	0.01520	-0.00007155

$$c_p = (109.91 + 0.0141T + 0.00001633T^2)$$

Mass of reactant = (109.2+2.57) = 111.7 kg/sec
Mass of product = 111.60 kg/sec
Total no of moles = 3.882 kmol
Apparent molar mass = 28.77 kg/kmol

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