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Theoretical Analysis of Off Design Performance Characteristics of Single Shaft Gas Turbine for Power Generation using Biomass Gasified Fuel

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ABSTRACT

Low calorific value fuels obtained in the biomass gasification having calorific value about 6-12 MJ/Nm3, are used for power generation using gas turbine, as they qualify for large power generation and also operate at low SFC. Gas Turbines operate at design point conditions at full load operation and when they run on part load, the operating point deviates from design point to prevent surging of compressor. When gas Turbine is running on LCV fuel such as Producer gas (CO+H2), the gas turbine operating point will change and this behaviour is transient and assessed by off design characteristic curves. Assessing the off design characteristics of gas turbine is tedious task and involves plotting of compressor & Turbine maps. In the present paper off design characteristics of single shaft gas turbine working on LCV fuel obtained from Biomass gasification of wood in down draft gasifier is simulated and modeled using fundamental equations of Thermodynamics and Thermal Turbo Machines. As per the specifications of OEM, gas turbines are basically built for operating using fuels such as Diesel & Methane, whose calorific value is in the range of 30-45 MJ/NM3, hence practically operating on LCV fuels such as Producer gas is slightly difficult. Hence a blend of Producer gas and Methane in various proportions is used and investigated for stable operation of single shaft gas turbine.

Keywords:—*Gasifier, Producer gas, LCV, Blend, off Design, Part Load Operation.*

I. INTRODUCTION

Gas Turbines are exhaustively used for power generation for peak load operations and it operates at low BSFC. A simple Gas Turbine cycle working on Brayton cycle consists of compress or, combustion chamber and a turbine as shown in the figure 1. The earlier simulation studies and modeling of gas turbines by various authors have indicated the parametric variation of SFC, Brake power, Brake Thermal Efficiency at various compression ratios. But in actual practice the operation of gas turbine at various loads which include full load and part load operation. The gas turbines are generally rated to operate with either Natural gas, low sulphurrated kerosene fuels and Aviation Turbine Fuel (ATF). These fuels have calorific value in the range of 24-36 MJ/ Nm3, whereas the producer gas obtained from bio mass gasification in a downdraft gasifier is about 6-12 MJ/Nm3. As calorific value is very less, such fuels adaptability is very difficult. The calorific value of Natural gas is about 24 MJ/Nm3 and AFR is about 12.5, so the size of combustion chamber using the LCV fuel such as Producer gas having calorific value of 6 MJ/Nm3, with AFR ranging between 0.9 to 1.1 is to be redesigned for s table operation of Gas Turbine. Though Energy Density is higher for Producer gas, it is risky to operate the gas turbine with producer gas. OEM's such as Siemens, GE, BHEL recommend the operation of gas turbine with conventional fuels such as Natural gas, ATF or diesel. Whereas the operation of gas turbine with producer gas involves study of load at various positions, such as full load and part load operation. In the present context significance of off design performance is presented and gas turbines table operation at steady state with blending of producer gas and Natural gas is presented. A simple gas turbine cycle shown in the figure 1, works on brayton/ Joule cycle. The Pressure, Temperature and mass flow rates at each state are indicated by Pi, Ti and Mi respectively. The Pressure, Temperature and mass flow rate of air at the inlet of compress or is P1= 1.01325 bar, T 1 = 298 K and M1 = 1 Kg/Sec. The Temperature of air at the outlet of compress or is function of pres sure ratio, is entropic efficiency of compress or and index of compression, given by

$$\frac{T2}{T1} = \left(\frac{p2}{p1}\right)^{\frac{\gamma-1}{\gamma}} \qquad (1.1)$$

The pressure ratio Rp = (P2/ P1) determines the exit condition of air leaving the compressor. The temperature of air leaving the compress or also depends on the is entropic efficiency of compress or and it is given by

$$\frac{T2\_actual}{T1} = [1 + \left[(Rp)^{\frac{\gamma-1}{\gamma}} - 1\right]/\eta_c] \qquad (1.2)$$

The actual temperature of air is higher than that is obtained without considering the is entropic efficiency. The air entering the combustion chamber is at higher temperature and higher pressure; self ignites the fuel entering the combustion chamber and produces the flue gases at higher pressure and temperature. The Heat addition occurs at is obaric conditions in the combustion chamber. The mass & energy balances to obtain the Turbine Inlet temperature (TIT) are given as a function of LCV, AFR, Cp_{air}, CP_{gas} and Temperature of air entering the combustion chamber.

$$M_{air} + M_{fuel} = M_{gas} \qquad (1.3)$$

$$M_{air*}\ Cp_{air*}\ (T_{2actual} - T_{ref}) + M_{fuel} * LCV = M_{gas}*Cp_{gas*}\ (T_3\text{-}T_{ref}) \qquad (1.4)$$

If combustion efficiency is considered, then the second term in the equation (1.4) is multiplied by the term (1-ηcomb). This yields TIT given by the relation

$$T_3 = T_{Ref} + [M_{air*}\ Cp_{air*}(\ T_{2actual} - T_{ref}) + M\ _{fuel}* LCV] / [M_{gas*}Cp_{gas}] \qquad (1.5)$$

The Turbine exit temperature (TET) determines the efficiency of gas turbine plant. Generally, TET at design point conditions is about 5400 C. But the TET is always higher and hence regenerative gas turbines are used in recovering the waste heat, to improve efficiency of gas turbine plant. The TET is given by the relation

$$T_4 = T_3 / (Rp)^{\frac{\gamma - 1}{\gamma}} \qquad (1.6)$$

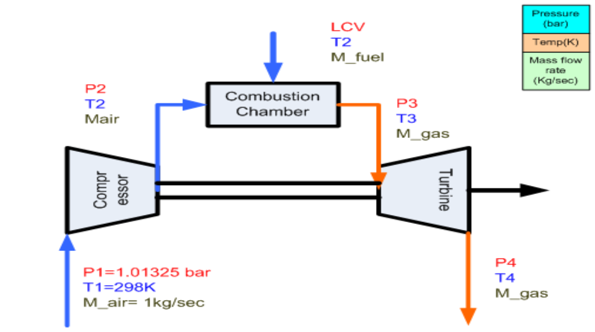

Figure 1 : Simple Gas Turbine Cycle

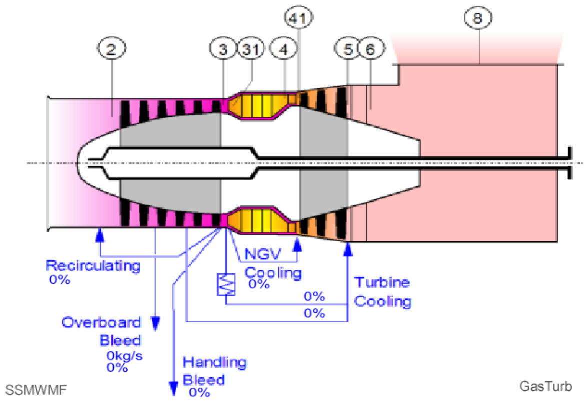

Figure 2 : Station Indication

Based on the equations 1.1 to 1.6, the designer determines the design point operation, which determines the thermal efficiency and air flow rate for given power demand. This information is required for design of turbo machinery and combustion systems of the gas turbine.

II. Literature Review

A Gas Turbine engine designed on the design point, usually achieve the design performance. But gas turbines have to operate for prolonged periods at the outside conditions from design point and this state is referred to as off design performance. Engine Off design conditions are due to varied Load and outside ambient conditions. Hence, for s table operation of Gas Turbine, it should not only achieve the performance at design point, but also at off Design. Determining off design performance involves interaction between compress or, combustion chamber and Turbine, known as component matching and component characteristics. When gas turbines operated with LCV fuels such as producer gas having calorific value of about 6-10 MJ/ Nm3, necessary energy input is drastically reduced. Hence components used with Generic Gas Turbines fuels, ATF, Natural gas and Dies el cannot be used with Producer gas as alternate fuel. There a re two options for the operation of gas turbine.

1. Select the compress or, Turbine which is suitable for the operation of LCV Fuel such as Producer gas
2. Blend the fuel and operate in dual fuel mode with necessary mix of Natural gas with producer gas in a definite proportion. Usually B40, B60, B80 are used with 40%, 60% and 80% producer gas.

The second option is investigated without altering the component selection. Producer gas obtained from down draft gasification has an average of 6-10 MJ/Nm3 of calorific value, where as Natural gas is about 35 MJ/ Nm3. The mixing proportions yields calorific value in the range of 12 - 25 MJ/ Nm3.

III. Off Design Performance Prediction of Singles Haft Gas Turbine

Off design performance is estimated with non dimensional parameters, such as Non-Dimensional Flow, Non-Dimensional speed and pressure ratio. These characteristics are normally plotted on non -Dimensional bas is so as to allow for variation of pressure, Temperature, speed and flow.

Non-Dimensional flow = m_1.s qrt(R_1T_1/γ)/P_1D^2 (3.1)

Non-Dimensional Speed = N_1/Sqrt(γ R_1T_1) (3.2)

$R_p=(P_2/P_1)$ (3.3)

Where m_1, T_1, P_1, and D are the inlet mass flow rate, Temperature, Pressure, and reference diameter of the compressor or Turbine. N1 is the rotational speed of the compressor or Turbine. P_2 is the discharge pressure of the compress or and γ is isentropic index with R as the particular gas constant of the air. The Non-Dimensional flow and speed are functions of Mach Number. For a given compress or, the flow area is constant and hence diameter D is no longer a variable.

3.1. Procedure

The required power output P, gas Turbine speed N_3, compress or inlet pres sure, P_1, Temperature, T_1, and humidity are specified. The assumptions made in the analysis is that inlet and exit pressure loses are negligible, with no air bleed for turbine b lade cooling.

Step-1 :Estimates (Seed values)

1. Estimate the compress or inlet mass flow rate, m_1
2. Estimate compress or Pressure Ratio R_p
3. Estimate Burner exit or Turbine In let temperature (TET)

Step-2 : Compressor

1. Calculate the Compress or inlet Non - Dimensional flow, given by equation 3.1
2. Determine the Compress or Non-Dimensional speed by Non-Dimensional flow and Pressure ratio by compress or characteristics curves.
3. Calculate the compress or exit mass flow as summing steady state conditions, exit Temperature from equation 1.1, exit pressure from equation 3.3 and compress or speed by Non-Dimensional speed relation 3.2.
4. Calculate the power input to the compressor.

Step-3 : Combustion chamber

1. Using the estimated value of TET, calculate the fuel flow rate, with calculated compressed air inlet to the combustion chamber and LCV of the fuel.
2. Calculate the combustion chamber exit p res sure using the pressure drop relation, expressed in terms of Non-Dimensional flow of compressor exit, Power load factor (PLF) and TET.
3. Calculate exit mass flow from the combustion chamber, in the absence of bleeds, by assuming steady state.

Step-4 : Turbine

1. Calculate the turbine in let Non-Dimensional flow, pressure ratio and Non-Dimensional speed of the turbine.
2. Determine the Turbine Non-Dimensional flow by Pressure ratio and Non-Dimensional speed from Turbine characteristics curves.
3. Determine the is entropic efficiency of the Turbine.

4. Calculate the Turbine exit Temperature using the relation 1.6

5. Calculate the power developed from the Turbine.

Step-5: Turbine flow Matching

1. Compare the Turbine Non-Dimensional flow calculated from step-4(1) with Turbine Non-Dimensional flow parameter obtained from Turbine operating Map from Step-4(2). If these values does not Match then return to Step-3. Assume a different value of TET or LCV of the fuel and repeat the steps from step -3 to step-5, till the turbine Non-Dimensional flow terms Match.

Step-6: Turbine power output Matching

1. Calculate the Power output of the Gas turbine

2. Compare the Calculated power output step-6(1) with the required power output. If they do not agree then go to step-2 and change the pressure ratio. Repeat the steps from step-2 to step-6, till the power matching occurs.

Step-7: Speed Matching

1. Compare the compress or speed, N1, Calculated in the step-2, with speed required by the load.

2. If these two parameters do not agree, go to step-1, estimate a different compress or mass flow rate, m1 and repeat the procedure till step-7.

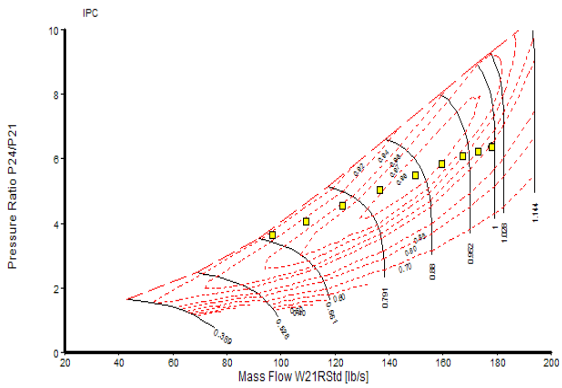

Figure 3. Compressor Characteristics

IV. RESULTS

The design point of operation using Natural gas having Calorific value of 38 000 KJ/ Nm3, with air mass flow rate of 30 kg/sec, Compress ion ratio of 6, Compress or is entropic efficiency of 0.85, Turbine inlet temperature of 1200 K, Turbine is entropic efficiency of 0.90, combustion chamber pres sure loss of 5% of inlet pressure to turbine, with mechanical efficiency of 98% and ambient conditions of 1.01325 bar, 288K is performed and presented. The design point operation is obtained using natural gas and subsequent off-design performance is obtained using blend of Natural gas and Producer gas. Producer gas obtained from down draft gasification of wood yields a syn gas having CO, H2, CH4 and CO2 in known proportions from earlier experimental results. The producer gas (also known as syn gas) has an range of Calorific Value of 6000 – 8000 KJ/ Kg. The gas turbine working on standalone producer gas will surge the compress or and the combustion chamber will starve from energy requirement. So an attempt is made to investigate the operation of gas Turbine with varying mix of producer gas and Natural gas in a mixing mode on the operation of gas Turbine for power generation.

Fuel properties at 288K, 1.01325 bar			
Fuel	LHV		Molecular-weight
	KJ/Kg	KJ/MN^3	
Natural gas	55998.7	38000	16.04
Producer Gas	6500	6284.6	23.55

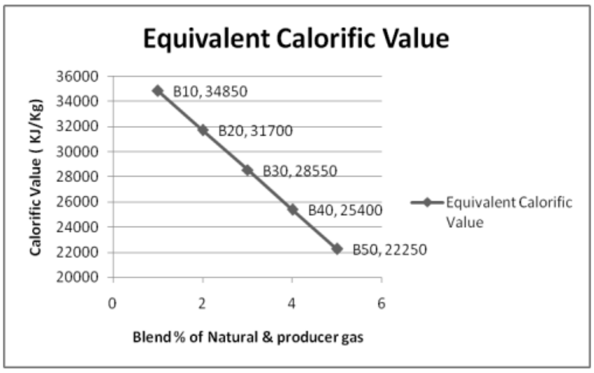

Figure 4 : Equivalent Calorific Value of Blends

4.1. Design Point and Off Design Points for Various Blends of Natural & Producer Gas

The design point operation of various blends obtained using the equations 1.1 to 1.6 and various design points for blends B0 to B100 are presented in the table 1.

V. CONCLUSIONS

The off Design performance of Single Shaft gas turbine is presented and design points for B0 to B100 is estimated. In most of the situations using low Calorific value fuel for running gas turbines, the flow and speed match is obtained by altering LHV and TIT, whereas power matching is slightly more complex as it deals with varying compress ion ratio. At lower compress ion ratios, ignition temperature for producer gas is difficult and it leads to misfires. In compare is on to design point operation of B0 the SFC for B100 has drastically increased. Gas Turbines are known to be Low SFC Gas Turbines, but for B100, it is not possible to operate as the SFC is about 6.5

Kg/KwHr. With variable pres sure ratio fro m 1.5 to 6.0, the SFC is decreased. The design point variation occurs at part Load operation and also at Variable LCV. When looked at part load operation for flow matching, with variable pressure ratio, the design point deviates introducing a very low TIT. But TIT at about 1000K may not ignite the Blend fuel. So without changing TIT and matching the flow requirements is complex, which decides even the Power and Speed matching. Earlier Researchers have introduced the concept of Non - Dimensional modeling and suggested to use commercial software applications such as GAST URB1 3.0 and GSP. Component matching, inclusive of flow, speed and power is a closure problem and complex to

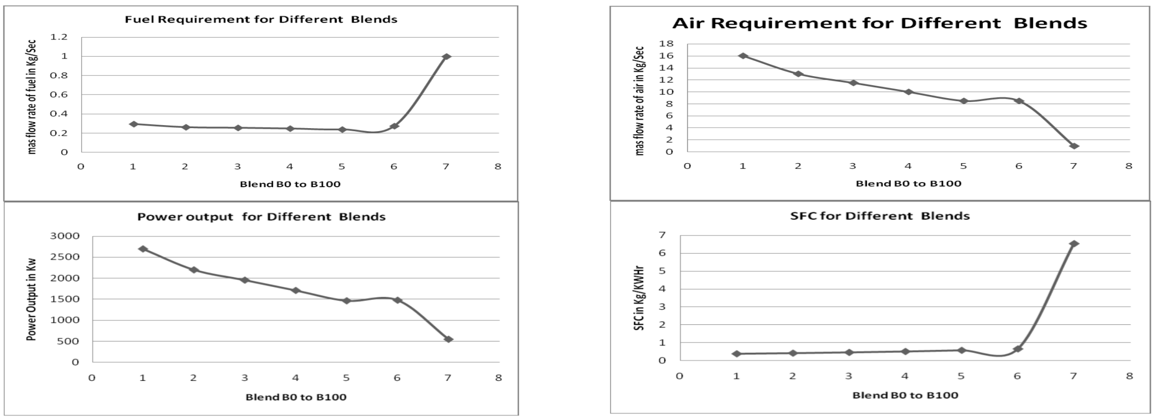

Figure 5. Variation of mass Flow rate of air, fuel, SFC and power output using different blends of NG & PG (# 1-B0, 2-B10, 3-B20, 4-B30, 5-B40, 6-B50, 7-B100)

arrive. Hence Future scope of work is proposed in this area of flow, speed and component matching

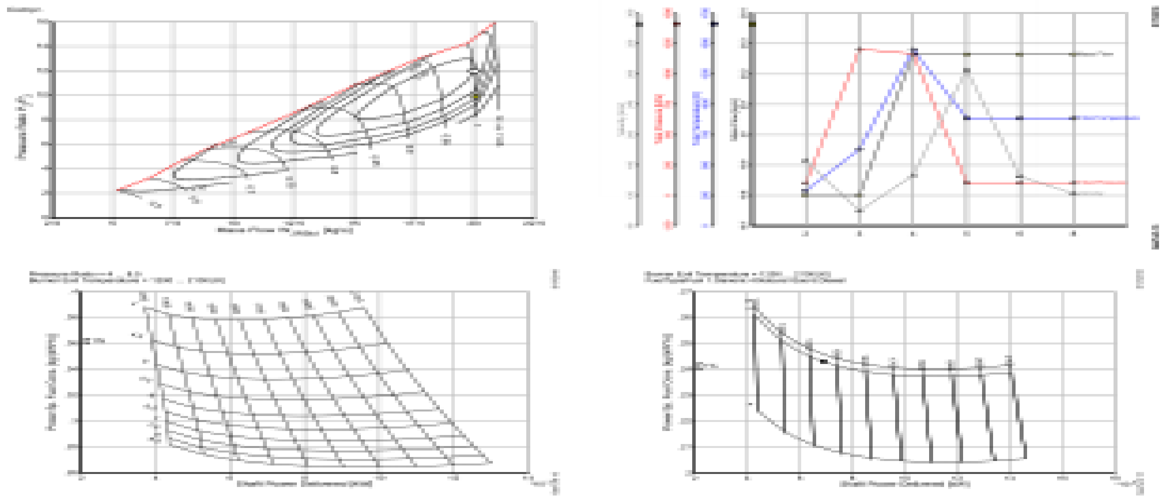

Figure 6 : Off design characteristics of Gas Turbine running on Producer gas and natural gas mix.

Table 1: The Design Point Operation of Various Blends Obtained using the Equations 1.1 to 1.6 and Various Design Points for Blends B0 to B100 are Presented

	Natural Gas (B0)	Producer Gas B100)	B10	B20	B30	B40	B50
T1	288	288	288	288	288	288	288
P1	1.01E+05	1.01E+05	1.01E+05	1.01E+05	1.01E+05	1.01E+05	1.01E+05
Isen_comp	0.85	0.85	0.85	0.85	0.85	0.85	0.85
Isen_Turb	0.9	0.9	0.9	0.9	0.9	0.9	0.9
LHV	38000	6500	34850	31700	28550	25400	22250
Rp	6	6	6	6	6	6	6
M_air	16	1	13	11.5	10	8.5	8.5
TIT	1200	1200	1200	1200	1200	1200	1200
T2	480.531	480.531	480.531	480.531	480.531	480.531	480.531
T2_act	514.5071	514.5071	514.5071	514.5071	514.5071	514.5071	514.5071
m_fuel	0.295859	1	0.262887	0.256569	0.248797	0.239002	0.274763
AFR	54.07979	1	49.45098	44.82217	40.19336	35.56455	30.93574
T4	766.9894	766.9894	766.9894	766.9894	766.9894	766.9894	766.9894
TET	810.2905	810.2905	810.2905	810.2905	810.2905	810.2905	810.2905
W_comp	3642234	227639.6	2959315	2617855	2276396	1934937	1934937
W_Turb	6337950	777860.2	5158336	4572484	3986066	3398861	3412770
W_Net	2695717	550220.6	2199021	1954628	1709670	1463924	1477833
Power	2695717	550220.6	2199021	1954628	1709670	1463924	1477833
SFC	0.395106	6.54283	0.43037	0.472545	0.523885	0.58774	0.669323

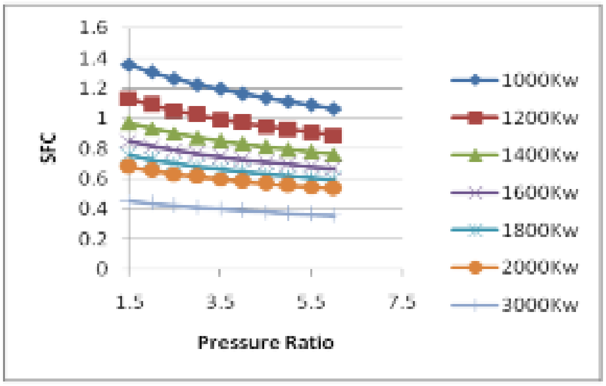

Figure 7: Compressor map, turbine Map, performance Characteristic curves at various TIT temperatures.

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