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Performance Analysis of Biomass Fuel Driven EFMGT Cycle

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Abstract: ***Biomass fuel as carbon neutral, abundant, domestic, cost effective is being reconsidered to fuel-up the power plant to produce electricity in clean way. But utilization of biomass fuel directly in existing conventional power plant causes problem in turbine such as erosion, hot corrosion, clogging and depositions [1]. As such combustion of biomass fuel outside the primary cycle eradicates potential hazards for turbine. In such a case indirectly fired micro gas turbine opens a door to biomass fuel as this technology is free from negative aspects of direct combustion as well as making micro gas turbine feasible to generate electricity in small scale at non-grid areas for individual consumer or group of consumers. In this research, the effect of different types of biomass fuel on operating parameters as well as on output electrical power of externally fired micro gas turbine (EFmGT)has been analyzed. The biomass fuels are categorized on the basis of air to fuel ratio (AFR) using stoichiometry combustion theory. It is found from results that parameters like air mass flow rate, compression ratio, heat exchanger effectiveness, turbine inlet temperature, combustion temperature, and temperature difference in heat exchanger affect the performance of EFmGT. Also types of biomass fuel have substantial impacts on these performance parameters as well as on electrical power output of EFmGT cycle.***

Keywords: Biomass, EFmGT, Electrical power, Energy, Polygeneration

I. INTRODUCTION

Biomass fuel as carbon neutral, abundant, domestic, cost effective is being reconsidered to fuel-up the power plant to produce electricity in clean way. But utilization of biomass fuel directly in existing conventional power plant causes problem in turbine such as erosion, hot corrosion, clogging and depositions [1]. Therefore, combustion of biomass fuel outside the primary cycle eradicates potential hazards for turbine. In such a case, indirectly fired micro gas turbine opens a door to biomass fuel as this technology is free from negative aspects of direct combustion as well as to generate electricity in small scale at non-grid areas for individual consumer or group of consumers(s).

Now-a-days distributed generation system based on micro gas turbine technology is being widely popular with a power range from 25kW to 500kW [2]. The function of micro gas turbine is to rotate compressor with high speed ranging from 30,000 rpm to 1, 20,000 rpm along with power production. Micro turbine offers numerous advantages compare to other small-scale technology such as high reliability due to small number of moving parts, high fuel flexibility, compact size, low maintenance, high temperature exhaust for heat recovery, low emission, acceptable power quality etc. In typical directly fired gas turbine, the combustion temperature can reach up to 1500°C resulting hazardous condition for the metallic turbine blades [3]. But in case of indirectly fired micro gas turbine, combustion gases do not come in direct contact with the turbine's working fluid. Therefore, turbine in EFmGT cycle remain safe during operation [4]. For such, EFmGT cycle consist of micro gas turbine with recuperator is a promising technology. Therefore, a wide range of fuel such as solid, liquid, gaseous fuel could be possible to burn in externally fired micro gas turbine (EFmGT) which unfolds plethora of opportunity for biomass in power generation.

In 1930, EFmGT was first experimented with coal but the technology has come under shade of light in very recent time and is now in the research and development stage. To analyze the performance of EFmGT on load condition is paramount to predict its dynamic behavior and as such mathematical modeling with simulation technique for instance, Aspen Plus, TRANSEO, Matlab\Simulink is being used to simulate the performance of this technology. Maksud et al. combined a thermodynamic model with a mechanical model of the rotor and transfer function-based control system model to develop a dynamic model for an EFmGT in Matlab/Simulink environment [5]. To examine the transient behavior of EFmGT, Alberto et al. studied the Externally Fired micro Gas Turbine (EFmGT) cycle at constant rotational speed and at constant Turbine Inlet Temperature (TIT) [6]. The temperature difference between hot side and cold side of the heat exchanger on the cycle power and efficiency was studied by Martin et al. which reports that 3% efficiency improvement could be achieved at 30K temperature difference reduction [7]. K.A. Al-attab et al. found 30% overall efficiency of a small-scale CHP designed with integrated gasifier in the combustion chamber where off-cut furniture wood block was used as fuel [8]. David et al. analyzed a downdraft gasifier and externally fired micro gas turbine for olive waste and found 70 kW electrical output powers at 20% electrical efficiency and 150 kW thermal powers output at 65% thermal efficiency respectively with a fuel consumption of 80-85 kg h-1 [9]. Amitabh et al. observed the effect of turbine inlet temperature (TIT), pressure ratio and temperature difference of heat exchanger on the thermal efficiency of EFmGT [10]. The thermodynamic performance of EFmGT cycle was evaluated by Soltani et al. on the basis of compressor pressure ratio,

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turbine inlet temperature and heat exchanger cold-end temperature difference and reported to observe a linear relation of energy efficiency with TIT and inverse relation with temperature difference in cold side of heat exchanger [11]. Baina et al. analyzed the effects of the contaminants presents in biomass derived gas on high temperature heat exchanger of EFmGT [12]. But there is no detailed study found addressing influence of biomass fuel types on the operating condition of EFmGT. Hence, the aim of this research is to investigate the operating parameters as well as electrical power output for various biomass fuel types at EFmGT cycle.

II. SYSTEM CONFIGURATION

A typical externally fired micro gas turbine consists of compressor, recuperator, turbine, a natural gas burner with the possibility to operate with biogas, and a water heat exchanger, high-speed generator, and power electronics to feed power to electrical loads. The basic block diagram has been shown in figure 1. The position of combustor in cycle differentiates externally fired micro gas turbine from directly fired micro gas turbine but both cycles works on Brayton thermodynamic cycle. The T-S diagram of EFmGT is shown in figure 2. Efficiency of the cycle could be improved with slight change in temperature difference between T2 and T6 in cold side and temperature difference between T3 and T5 in hot side which also increases the size of the heat exchanger and associated costs. [7]

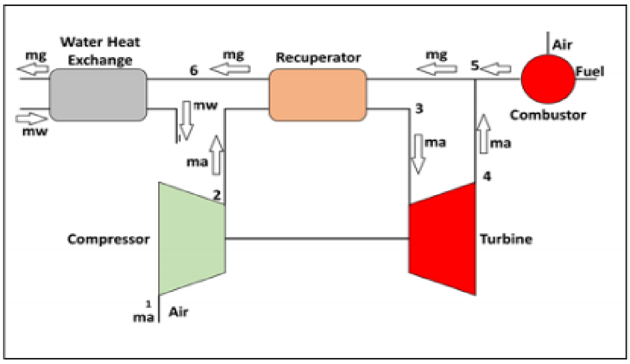

Figure 1: Block diagram of externally fired micro gas turbine (EFmGT)

In EFmGT cycle, the compressed air at cold side of heat exchanger absorbed heat from hot combustion gases from hot side of heat exchanger. This heated compressed air works as working medium which hit the turbine for rotation. The expanded air leaving turbine blade is mixed with the hot flue gases from the combustion chamber. In addition, excess air has to be injected in combustor to control flame instability. This hot flue gases passes successively through recuperator and a water heat exchanger where waste heat is restored in form of hot water respectively.

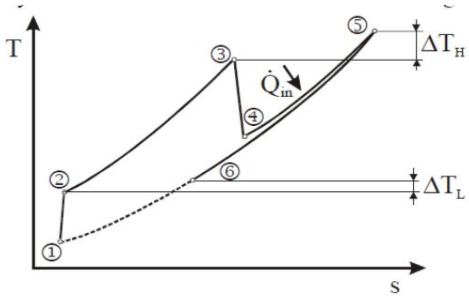

Figure 2: T-S diagram of Externally Fired micro Gas Turbine

The model is designed and simulated to predict the dynamic behavior of externally fired micro gas turbine for 100 kW electric outputs. The model consists of five parts; the thermodynamic part, the controllers, temperature and speed control, the fuel system and the shaft dynamics. The thermodynamic part consists of compressor, turbine, recuperator, combustor have been developed using thermodynamic equations while transfer function have been used for control systems [13]. Finally, the developed model has been merged with mechanical model of rotor.

III. MODEL VALIDATION

Design data of Turbec T100 micro gas turbine as given in table 2.1 has been used in this study and validation has been done against data given in table 2.2. Model output power was 3kW at efficiency of 30% [7].

Table I: Comparison between simulated data and measured data

Net electric-output	**100**	**kW**
Net electric-efficiency, ISO	30	%
Fuel type	Natural gas	
Mass flow air	0.7780	kg\sec
Mass flow, natural-gas	0.0069	kg\sec
Mass flow, exhaust-gas	0.7849	kg\sec
Pressure ratio	4.5	
Efficiency compressor	0.768	
Efficiency turbine	0.826	

The validated data are compressor output temperature (T2), turbine inlet temperature (T3), turbine outlet temperature (T4), inlet temperature of heat exchanger from hot side (T5) for natural gas as fuel. The deviation of simulated data ranges from 0- 17%. Smallest deviation is found for compressor output temperature accounts to 0% while maximum deviation occurs for T4 which is 17.24 percent. The electrical output power is 3 kW and electrical efficiency is 30% for validated model.

Table II: Comparison between simulated data and measured data

	Reference data [7]	**Simulated data**	**Relative error (%)**
T2	487K	487 K	0
T3	1223K	1027 K	16
T4	923 K	763.8 K	17.24
T5	1230 K	1033 K	16
T6	-	949 K	-

A. Simulation with biomass fuel

After validation, the model is run with eight (8) different types of biomass fuels are provided in table 3.1 with their ultimate composition. Ultimate analysis breaks down the fuel into elemental component such as C, H, N, S and O. Carbon, Oxygen, Hydrogen are main constituents of biomass and Nitrogen, sulfur, chlorine are found in less percent in biomass. Heating value of biomass is in strong correlation with the moisture content since presence of moisture effect the former inversely.

The stoichiometry air fuel ratio is computed from the composition of hydrocarbon fuel using the following equations.

$$C_nH_m + (n + \frac{m}{4})(O_2 + 3.78\,N_2) \rightarrow n\,CO_2 + \frac{m}{4} H_2O + 3.78\,(n + \frac{m}{4}) \quad (1)$$

Thus, one mole of fuel C_nH_m is required to mix with 3.78 $(n+\frac{m}{4})$ mol of air to ensure that no unburned fuel left the combustion zone.

Table III: Biomass fuel composition [14]

Fuel type	Ultimate Analysis					LHV
	C (%)	H (%)	O (%)	N (%)	S (%)	KJ\Kg
Animal Waste	35.10	5.30	38.70	2.50	0.40	13,400
Rice Husk Patni-23	38.92	5.10	37.89	2.17	0.12	15,670
Tea waste	48.60	5.50	39.50	0.50	-	17,100
Wheat Straw	45.50	5.10	34.10	1.80	-	18,910
Switch grass	47.52	5.96	44.8	0.37	-	19,070
Cotton stalk	39.47	5.07	39.14	0.45	0.16	20,050
Coconut shell	50.22	5.70	37.43	-	-	20,490
Wood Pine Chips	52.1	6.1	41.44	0.30	-	21,021

For proper combustion, the air to fuel ratio (AFR) for each types of biomass are required to be known. The air to fuel ratio have been calculated according to stoichiometry combustion theory which are plotted against SFC shown in the figure 3.1. For biomass fuels, air to fuel ratio usually lies in the range of 5-10. It is also found that air to fuel ratio decreases with corresponding increase in the specific fuel consumption. Assuming constant gas content at 16% during the study, the specific fuel consumption is inversely related to air to fuel ratio.

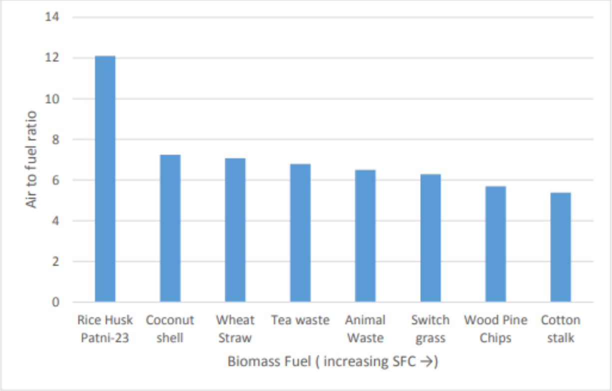

Figure 3: Air to fuel ratio (AFR) of biomass fuels at constant gas content

IV. RESULT AND DISCUSSION

A. Effect of air mass flow

Figure 4(a) shows compressor power against air mass flow rate at different input temperature. Compressor power remain similar irrespective of fuel types studied. Compressor power increases with air mass flow rate for different air temperature. The temperature of air is varied between 15°C to 35°C. Any change in load condition brings change in fuel consumption and consequently air intake is varied to adjust the condition.

Figure 4 (b) reveals that the power developed at turbine varies with air mass flow rate (m_a) for all types of fuel studied. Biomass fuel namely Rice Husk Patni-23, Coconut Shell, Wheat Straw, Tea Waste, Animal Waste, Switch Grass, Wood Pine Chips and Cotton Stalk have been considered in this study. For all fuel, Turbine power increases sharply until air mass flow rate (m_a) reaches to 2.29kg/s, afterward the rate of increment gets slower. The calculated AFR of Rice Husk Patni-23 is 12.1 while Coconut Shell and Wheat Straw are 7.24 and 7.07 respectively. AFR of Tea Waste, Animal Waste and Switch Grass are in the range of 6.79 to 6.28. AFR for wood pine chips and cotton stalk have found 5.69 and 5.38 respectively. Since AFR of taken biofuels are in close band of value, result analysis are shown only for rice husk patni-23, wheat straw, switch grass and cotton stalk in figure 4.1. Highest turbine power is found for Cotton stalk with AFR 5.28 while lowest for rice husk patni-23 with AFR 12.1. This is due to specific fuel consumption decreases with increasing AFR and consequently, mechanical power developed in turbine decreases with fuel of larger AFR

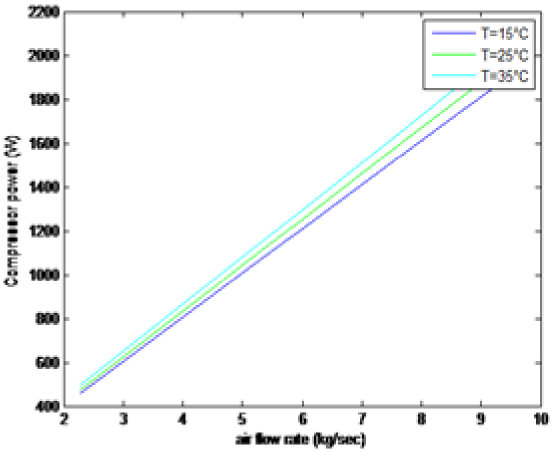

Figure 4 (a) Effect of air mass flow rate on compressor power at different ambient temperature

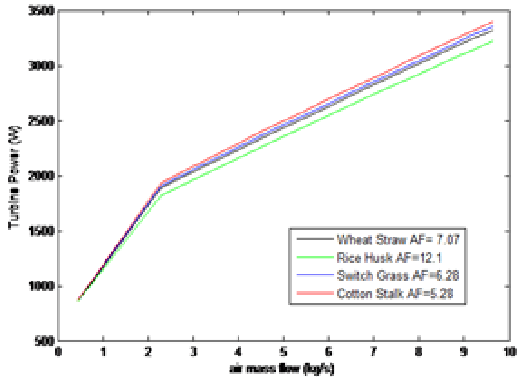

Figure 4 (b) Effect of air mass flow on turbine power for biomass fuel types

Figure 4(c) illustrates net electrical power output against air mass flow for all said fuels. It reveals that net electrical power gets its maxima at ma =2.29 kg/sec before starting to decay. This is owing to high power consumption by compressor despite of lower power development in turbine. Therefore, electrical power output starts to decrease. The maximum 1.255 kW power is found for cotton stalk. Besides, net electrical power decreases with fuels corresponding to higher AFR.

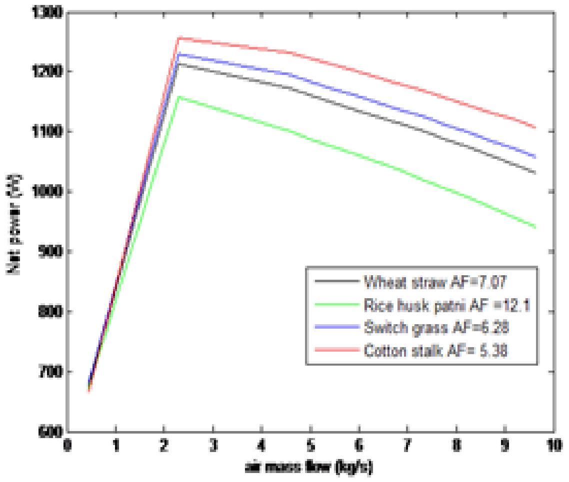

Figure 4 (c) Effect of air mass flow on the net power at ambient temperature T= 15°C

B. Effect of Turbine Inlet Temperature

At specific temperature difference in heat exchanger (ΔT_H), it is clearly shown in Figure 5 that electrical power output of EFmGT varies linearly with turbine inlet temperature (TIT) change. Also fuel having higher air-to-fuel ratio (AFR) produces more power compare to lower AFR fuel .

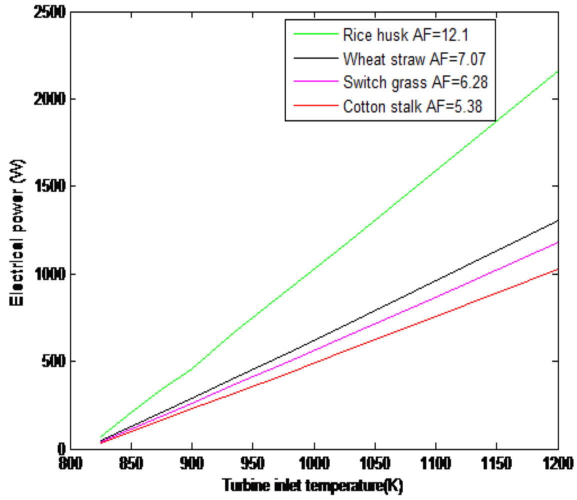

Figure 5: Electrical power as function of turbine inlet temperature and AFR at ΔTH =47K

C. Effect of Compressor pressure ratio

Figure 6 illustrates the impact of pressure ratio on electrical power for biomass fuels with different AFR. It is found that electrical power begins to rise at compression ratio = 2 and then get its maxima at 3.2 before falling drastically at temperature difference in heat exchanger is ΔT_H=47K for 100kW capacity. For all types of fuel, inlet air temperature is considered T1=15° C. It is also seen that fuel having higher AFR response faster to the compression ratio change.

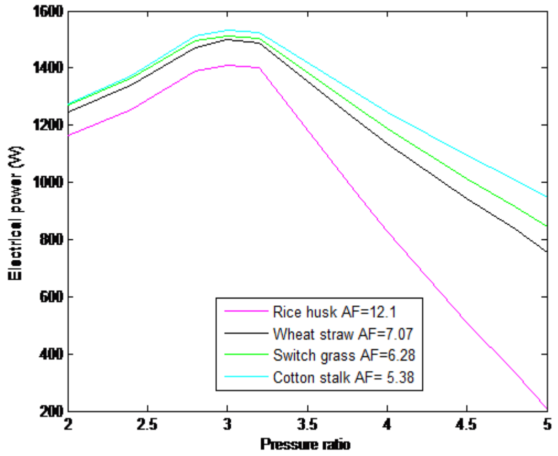

Figure 6: Electrical efficiency as a function of compressor ratio

D. Effect of heat exchanger effectiveness

Figure 7 illustrates that electrical power output gets directly affected by heat exchanger (HEX) effectiveness. Higher effectiveness implies higher heat transfer from flue gas to working air in heat exchanger rising turbine inlet temperature and consequently output power upscales. Effectiveness of heat exchanger is normally lower for EFmGT due to fouling of combustion gases increasing the thickness of deposit material in the heat exchanger. Besides, electrical power output is higher for fuel of lower AFR.

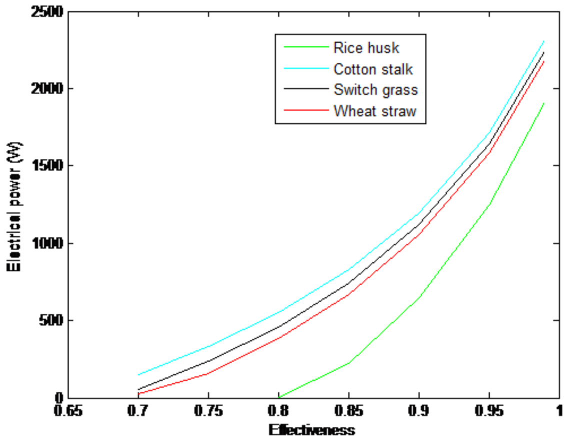

Figure 7: Heat exchanger effectiveness versus electrical power

E. Effect of heating value of fuel

The figure 4.7 illustrates the effect of the lower heating value over electrical power output for all the fuels studied.

Result reveals that cycle power is not related to the heating value of fuel in EFmGT. It is generally assumed that power output is directly related to the heating value of fuel. Fuel with higher heating value is likely produce higher temperature and hence to produce more electricity. Though this is true in some extent for some fuel but not for all.

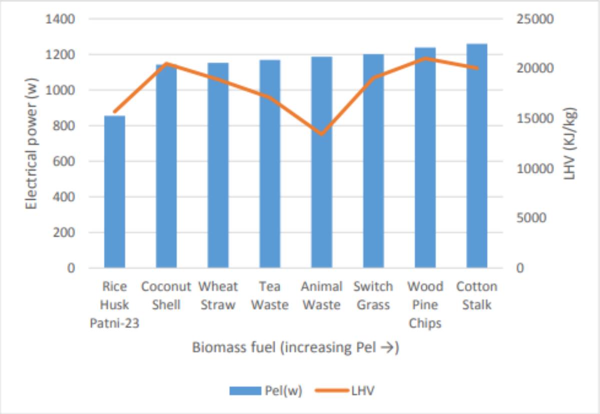

Figure 8: Effect of lower heating value on electrical power

V. CONCLUSION

The parameter like air mass flow rate, compression ratio, heat exchanger effectiveness, turbine inlet temperature, combustion temperature, temperature difference in heat exchanger are found performance setting parameter for externally fired micro gas turbine. But these factors are still rarely addressed for EFmGT in literature. Therefore, these parameters are studied in this research for eight types of biomass fuels in EFmGT. The following observations from this study have been found:

- Compressor power and turbine power increases with increase in air mass flow rate (ma). The rise of turbine power slows down after ma reaches at 2.2 kg/s but the compressor power continues to increase. Therefore, net electrical power increases until a certain value of m_a and after that net electrical power starts to decrease. And fuels with higher value of AFR are tends to produce less power with variation of air mass flow rate (m_a).
- Electrical output power increases with increase in compression ratio for given temperature difference in heat exchanger. Since the compression ratio increases the air temperature which in turn raises turbine power. Consequently, electrical power output increase until a certain point and afterward output power drops with increase of compression ratio. Fuels with higher AFR respond faster to the change in compression ratio.
- Although turbine inlet temperature (TIT) in EFmGT cycle is smaller than usual due to lower value of effectiveness in heat exchanger but it greatly influences power output of this cycle.
- Effectiveness and temperature limit of heat exchanger are vital points for EFmGT operation. The operational temperature of heat exchanger is limited to 650°C in EFmGT. Therefore, excess air is required to supply into combustion chamber to lower the hot side inlet temperature of heat exchanger. This greatly hinders the performance of EFmGT. Better performance is shown by the fuel with lower AFR.
- It is generally assuming that electrical power output is directly related to the heating value of fuel, higher heating value of fuel is likely produce more electricity. Such is not true for all case.

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