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Modeling of gas turbine operated by municipal solid waste

Dr. Kamaljyoti Talukdar[1]
[1](*Assistant Professor, Department of Mechanical Engineering, Bineswar Brahma Engineering College, Kokrajhar, Assam, India)*
Corresponding Author: Dr. Kamaljyoti Talukdar

Abstract: *With rapid improvement in life style of society, waste generation like municipal solid waste(MSW) is increasing which needs constructive utilization. In this paper gas turbine system is operated by burning municipal solid waste (MSW) as fuel in combustion chamber. The power output of gas turbine system is 1 MW operated throughout the year in Kolkata city, West Bengal, India. The excess power generated by gas turbine is used for operating the compressor. The air flow rate and fuel (municipal solid waste) flow rate are maintained in such a way that 1 MW power is obtained throughout the day. The temperature of air entering the compressor is ambient temperature of Kolkata city and gas coming out from combustion chamber is considered at a temperature of 1000 K. In Kolkata city the study is made for the month of January (minimum temperature) and May (maximum temperature) available in a year. It is found that air flow, fuel flow, turbine work and compressor work decreases from 1:00 AM till 5:00 AM, increases till 3:00PM and again decreases till 12:00AM. The thermal efficiency of the gas turbine plant increases from 1:00AM till 5:00AM, decreases till 3:00PM and again increases till 12:00 AM.*

Keywords : *Combustion chamber, Compressor, Gas turbine, Month, Municipal Solid Waste (MSW)*

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I. Introduction

Gas turbines are engines which provide power by burning fuel in combustion chamber. The fuels may be anything like coal, petroleum, natural gas etc. which may be conventional and non conventional fuels. Gas turbines can also be operated by adjusting it as topping or bottoming cycles. In reference [1] authors used exhaust gas from solid oxide fuel cell (SOFC) to operate gas turbine. In reference [2] authors presented a discussion about the gas turbine modeling approach and the gas turbine component matching between the compressor and the turbine by superimposing the turbine performance characteristics on the compressor performance characteristics with suitable transformation of the coordinates. Use of black liquor, the lignin-rich byproduct of kraft pulp production, after gasification in boiler/steam turbine cogeneration systems at pulp mills for operating gas turbines is presented in [3]. In reference [4] authors calculated the performance, cost and prospects for commercial development of two biogas-gasifier/gas turbine (BIG/GT) systems one using solid biomass fuel (e.g., wood chips), the other using kraft black liquor. In reference [5] author discussed the performance of gas turbine by injecting exhaust-heat-generated steam into gas turbines for power augmentation.

In the present paper the gas turbine is being operated by burning municipal solid waste generated by people residing in Kolkata city in West Bengal state in India. Municipal solid waste generated is utilized for constructive purpose by producing 1 MW power by gas turbine. Also waste disposal problem of solid waste is minimized.

II. System Layout

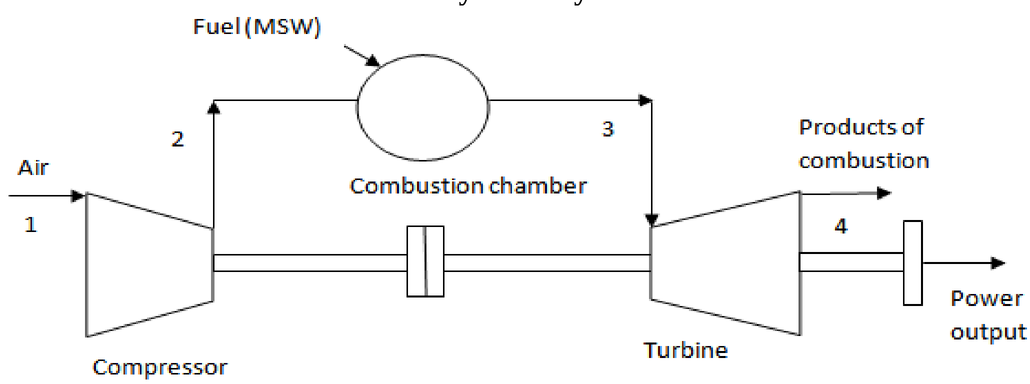

Fig 1: Typical GT plant operated by MSW

In fig. no. 1, it shows the typical gas turbine plant operated by municipal solid waste in combustion chamber for generating power throughout the day and year. Required air flow for generating power is passed through air compressor at ambient temperature of Kolkata city throughout the day from 1:00AM to 12:00AM. That air is sent to combustion chamber and required fuel (MSW) in combustion chamber is supplied. The combustion gas formed after burning of MSW with air coming out at a temperature of 1000 K from combustion chamber is sent to GT. Excess power is generated by GT(>1 MW) and hence excess power is sent to compressor for running the compressor. The system is adjusted in such a way that power generated by GT minus power consumed by compressor is always 1 MW throughout the day. The combustion gas after coming out from GT is rejected to atmosphere. For analysis two months i.e. May and January are taken, because month May and January have maximum and minimum ambient temperature respectively and if the system works well in these two months it will work throughout the year.

III. Modeling of Gas Turbine

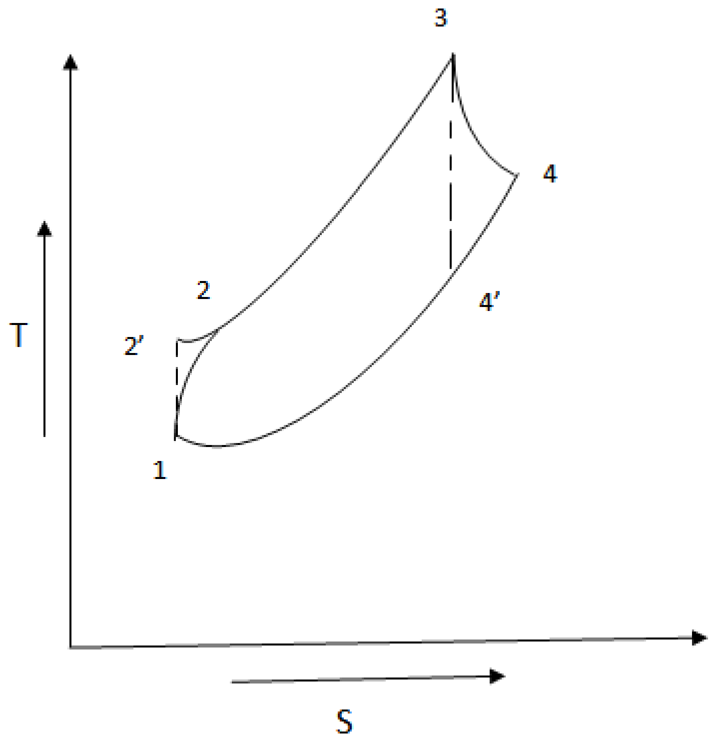

Fig 2: Temperature- entropy(T-S) diagram of fig. no. 1

Fig. 2 shows temperature-entropy (T-S) diagram of GT plant. Process 1-2' shows isentropic compression of air in compressor. T_1 is the air inlet to compressor at ambient temperature of Kolkata city [6]. $T_{2'}$ is the temperature given by equation no.1 [7]:

$$T_{2'} = T_1 \times \left[\frac{P_2}{P_1}\right]^{\frac{\gamma_i - 1}{\gamma_i}} \tag{1}$$

$\frac{P_2}{P_1}$ =pressure ratio (considered 6 in present study), γ_i=1.4 k J/ kg. K [7].

Process 1-2 shows actual compression of air given by equation no. 2 [7]:

$$T_2 = T_1 + \frac{T_{2'} - T_1}{\eta_C} \tag{2}$$

η_C= 0.85 [8].

Process 2-3 is the combustion process taking place in combustion chamber. Temperature of combustion gas (T_3) coming out from combustion chamber is considered constant (1000 K).

Process 3-4' is the isentropic expansion of combustion gas in GT and temperature ($T_{4'}$) is given by equation no. 3 [7]:

$$T_{4'} = T_3 \times \left[\frac{P_4}{P_3}\right]^{\frac{\gamma_f - 1}{\gamma_f}} \tag{3}$$

$\frac{P_4}{P_3}$ = pressure ratio (considered $\frac{1}{6}$ in present study), γ_f=1.33 k J/kg. K [7].

Process 3-4 shows actual expansion of combustion gas in GT given by equation no. 4 [7]:

$$T_4 = T_3 - \eta_T \left(T_3 - T_{4'}\right) \tag{4}$$

η_T=0.9 [9].

Now mass flow rate of air, fuel flow rate, turbine work, compressor work, net work and thermal efficiency are given by equations 5,6,7,8,9 and 10 respectively [7]:

$$\dot{m}_a = \frac{1000}{\left[C_{pg} \times \left(T_3 - T_4\right) + \frac{C_{pg} \times \left(T_3 - T_2\right)}{LHV_{MSW} \times \eta_{comb}} \times C_{pg}\left(T_3 - T_4\right)\right] - \left[\frac{C_{pa}}{\eta_m} \times \left(T_2 - T_1\right)\right]} \tag{5}$$

C_{pg}=1.147 k J/ kg. K [7], η_{comb}=0.98 [7], η_m=0.95 [8].

The composition of MSW is as follows taken from [10]: carbon-25%, hydrogen-3%, oxygen-20%, sulphur-0.3%, nitrogen-0.5%, ash-25%, moisture -25%. The LHV_{MSW} is calculated from [11].

$$\dot{m}_f = \frac{\dot{m}_a \times C_{pg} \times \left(T_3 - T_2\right)}{LHV_{MSW} \times \eta_{comb}} \tag{6}$$

$$W_T = \dot{m}_a \times C_{pg}\left(T_3 - T_4\right) + \dot{m}_f \times C_{pg}\left(T_3 - T_4\right) \tag{7}$$

$$W_C = \left[\frac{\dot{m}_a \times C_{pa} \times \left(T_2 - T_1\right)}{\eta_m}\right] \tag{8}$$

C_{pa}= 1.005 k J/kg.K [7].

$$W_{net} = W_T - W_C = 1000\,kW \tag{9}$$

$$\eta_{thermal} = \left[\frac{W_{net}}{\dot{m}_f \times LHV_{MSW}}\right] \times 100 \tag{10}$$

IV. Results and Discussions

With increase in ambient temperature, T_2, $T_{2'}$, T_4, $T_{4'}$ goes on increasing.

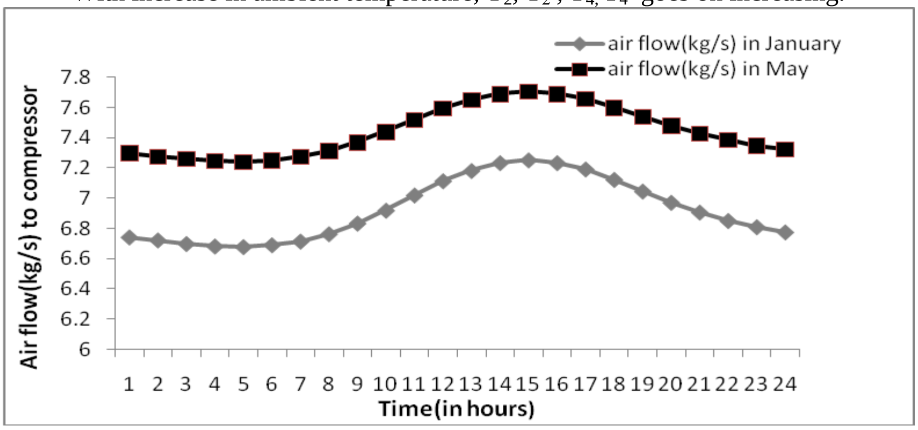

Fig 3: Variation of air flow rate to compressor w.r.t hours

Fig. 3 shows the air flow rate in compressor. It is seen that from 1:00 hour the air flow required goes on decreasing till 5:00 hours, increases till 15:00 hours and again decreases till 24:00 hours for both months January and May. It is due to the fact that ambient temperature of Kolkata city goes on decreasing from 1:00 hour till 5:00 hours, increases till 15:00 hours and again decreases till 24:00 hours. Hence T_4 and T_1 go on decreasing from 1:00 hour till 5:00 hours, increases till 15:00 hours and again decrease till 24:00 hours. In equation no. 5, the denominator part goes on increasing from 1:00 hour till 5:00 hours, decreases till 15:00 hours and again increases till 24:00 hours keeping numerator constant. Therefore such a trend shown in fig. 3 is observed. Air flow rate is greater in month of May than the month of January because month May has higher ambient temperature than January. Hence decrease in denominator part of equation no. 5 is more for the month of May than January leading to such variation shown in fig. no. 3.

Fig. 4 shows fuel flow rate (MSW) in combustion chamber. Same trend is seen as shown in fig. 3. In equation no. 6, (T_3-T_2) goes on increasing and air flow rate goes on decreasing from 1:00 hour to 5:00 hours, but effect of decrease in air flow rate is more dominant than (T_3-T_2) increase, hence fuel flow rate goes on decreasing from 1:00 hour to 5:00 hours. (T_3-T_2) goes on decreasing and air flow rate goes on increasing from 5:00 hours to 15:00 hours, but effect of increase in air flow rate is more dominant than (T_3-T_2) decrease, hence fuel flow rate goes on increasing from 5:00 hours to 15:00 hours. And again (T_3-T_2) goes on increasing and air flow rate goes on decreasing from 15:00 hours to 24:00 hours, hence fuel flow rate goes on decreasing from 15:00 hours to 24:00 hours due to the same reason mentioned above for 1:00 hour to 5:00 hours. Month May has higher fuel flow rate than January due to higher effect of mass flow rate of air than (T_3-T_2).

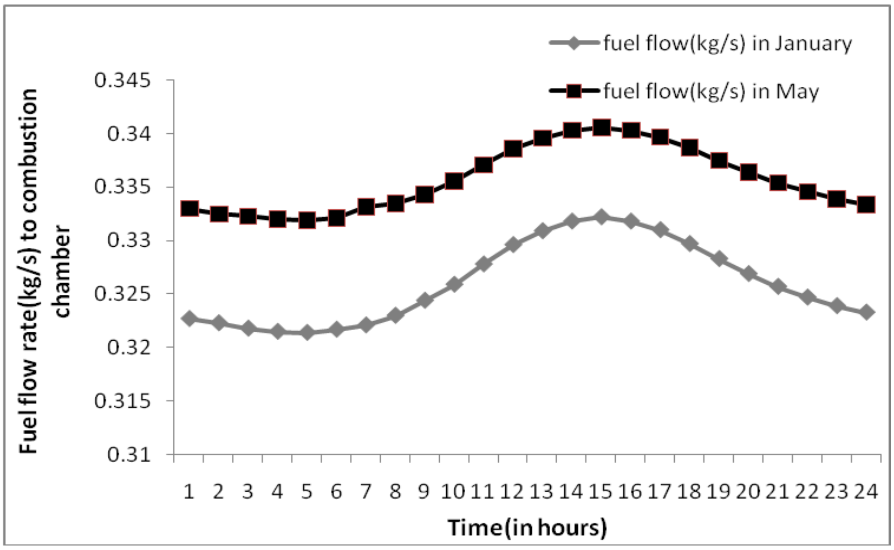

Fig 4: Variation of fuel flow rate(MSW) to combustion chamber w.r.t hours

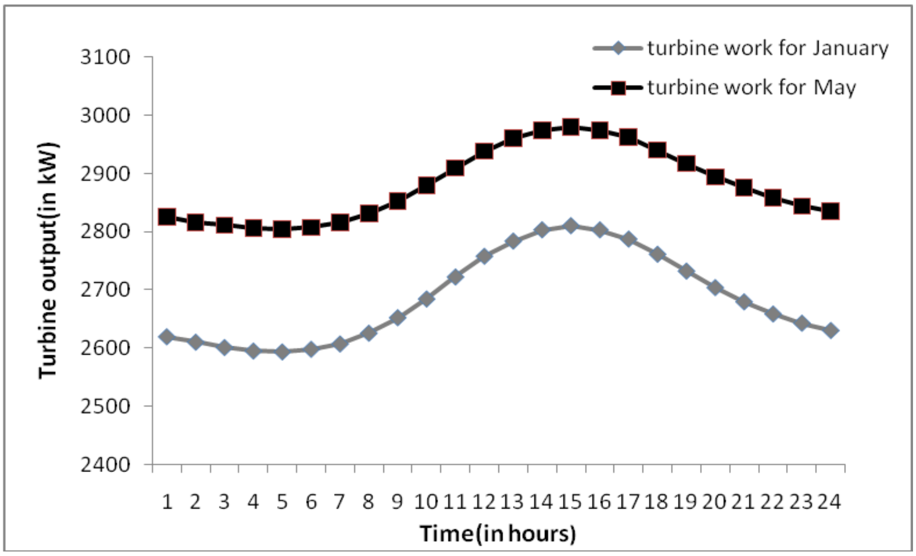

Fig 5: Variation of turbine power output w.r.t. hours

Fig. 5 shows turbine power output. Similar trend is seen as mentioned above. In equation no. 7, (T_3-T_4) goes on increasing and air flow rate goes on decreasing from 1:00 hour to 5:00 hours, but effect of decrease in air flow rate is more dominant than (T_3-T_4) increase, hence turbine power output goes on decreasing from 1:00 hour to 5:00 hours. From 5:00 hours to 15:00 hours (T_3-T_4) goes on decreasing and air flow rate goes on increasing, but effect of increase in air flow rate is more dominant than (T_3-T_4) decrease, hence turbine power output goes on increasing from 5:00 hours to 15:00 hours. And again from 15:00 hours to 24:00 hours (T_3-T_4) goes on increasing and air flow rate goes on decreasing hence turbine power output goes on decreasing due to the same reason mentioned for 1:00 hour to 5:00 hours. Month May has higher turbine power output than January due to higher effect of mass flow rate of air than (T_3-T_4).

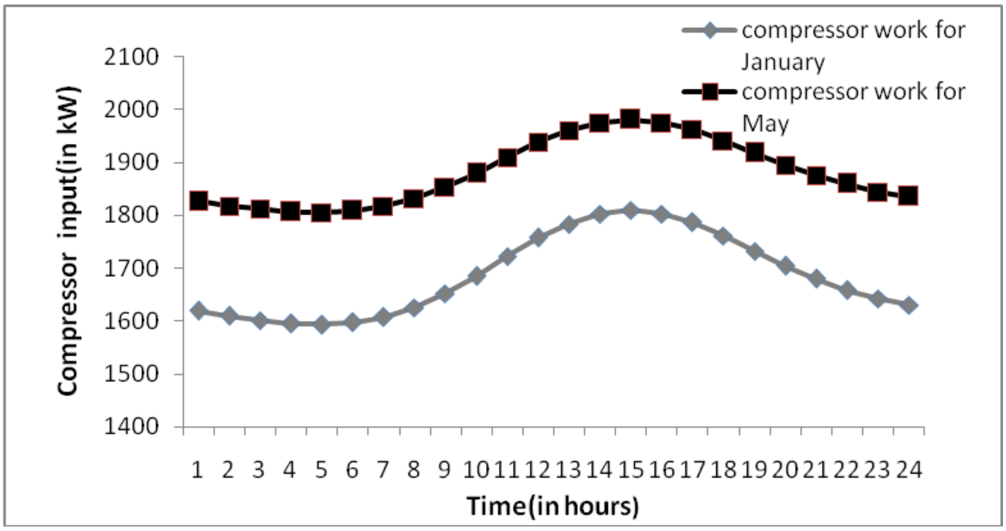

Fig 6: Variation of compressor power input w.r.t. hours

Fig. 6 shows compressor power input. Similar trend is seen as that discussed above. From equation 8, it is seen that from 1:00 hour to 5:00 hours compressor input power decreases due to decrease of air flow rate, increases from 5:00 hours to 15:00 hours due to increase in air flow rate and again decreases till 24:00 hours due to decrease of air flow rate. (T_2-T_1) remains almost constant because with change in ambient temperature (T_1), T_2 also changes accordingly. Month May has higher compressor power input than January due to higher effect of mass flow rate of air.

Fig. 7 shows the thermal efficiency of the complete system. It is seen that efficiency increases from 1:00 hour to 5:00 hours, decreases from 5:00 hours to 15:00 hours and again increases to 24:00 hours due to the fact that fuel flow rate in the denominator part (equation 10) decreases from 1:00 hour to 5:00 hours, increases till 15:00 hours and again decreases to 24:00 hours. The net power (W_{net}) which is 1000 kW and LHV_{MSW} remains constant. Month January has higher efficiency than May due to lower mass flow rate of fuel in denominator part of equation no. 10 than the month of May.

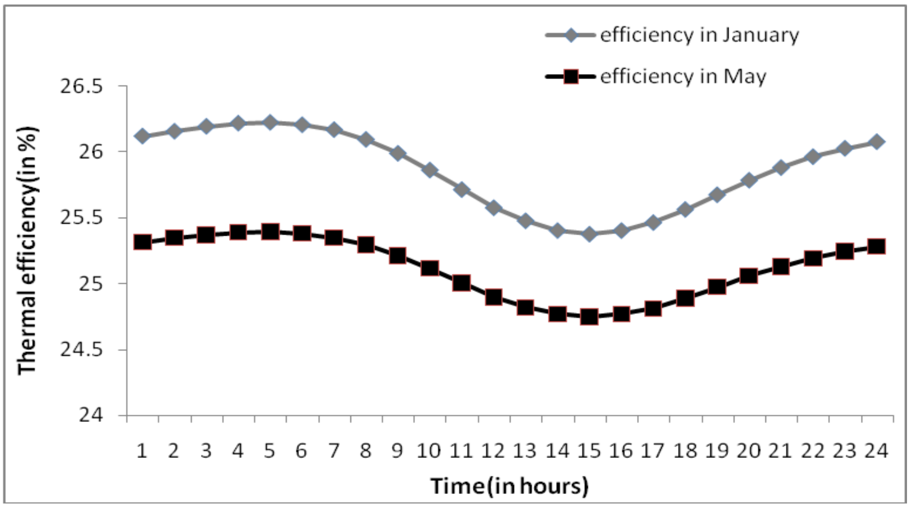

Fig 7: Variation of thermal efficiency of GT plant w.r.t. hours

V. Conclusion

The work presented in this paper is to operate a GT plant with MSW as fuel. MSW is generated in large quantity and in future this waste is going to increase in large scale. Hence this waste is used for generating 1 MW power. For operating the GT plant air at ambient temperature for Kolkata city located in India is taken by compressor and MSW is supplied to combustion chamber. Based on the observations made above it is seen that as air at ambient temperature to compressor increases, mass flow rate of air, mass flow rate of fuel, turbine power output and compressor input power increases. With the increase of ambient air temperature, thermal efficiency decreases.

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Nomenclature

C_{pa}	specific heat of ambient air (k J/kg. K)
C_{pg}	specific heat of combustion gas (k J/kg. K)
GT	gas turbine
LHV	lower heating value
$\dot{m}_a$	mass flow rate of air (kg/s)
$\dot{m}_f$	mass flow rate of fuel (kg/s)
MSW	municipal solid waste
P	pressure (bar)
T	temperature (K)
W_C	compressor work (k W)
W_T	turbine work (k W)
γ_i	ratio of specific heat of air
γ_f	ratio of specific heat of combustion gas
η_c	isentropic efficiency of compressor
η_T	isentropic efficiency of turbine
η_{comb}	combustion efficiency of combustion chamber
η_m	mechanical transmission efficiency of power from turbine to compressor
$\eta_{thermal}$	thermal efficiency of GT plant

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