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Effect of ambient temperature on the performance of gas turbine with cogeneration system

Effect of ambient temperature on gas turbine

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Abstract — *In the commercial sector, power demands peak in the summer daytime because of high space cooling demands, and cogeneration plants are required to produce maximum power to meet their demands. However, gas turbine with cogeneration plants have the disadvantage of decrease in maximum power output in the summer daytime, which reduces the availability of gas turbine. In the present study, for a further understanding of the effect of the ambient temperature and inlet air temperature on the performance of gas turbine, an analysis based on 24 hours data has been carried out. The main objective is to determine the effect of variation in ambient air temperature on the gas turbine output and heat rate. The results shows that when ambient temperature increases, gas turbine output decreases. It was also found that when ambient temperature increases, heat rate increases. It was observed that the maximum output of 30.73 MW is produced at 7.00 a.m. (early morning) when ambient temperature is recorded 24.2 ^{0}C, while the minimum output of 26.85 MW is produced at 15.00 p.m. (noon) when ambient temperature is recorded 36.7 ^{0}C. It was also noticed that the overall gas turbine output variation was 4 MW corresponding to overall temperature variation of 13 ^{0}C.*

Keywords- *Gas turbine output, heat rate, ambient temperature, thermal efficiency, overall efficiency*

I. INTRODUCTION

Gas turbines have been used for power generation in several regions in the world. In recent years, the world is facing problem of rapid depletion of fossil fuel and environmental disruption [1]. One of the possible solutions is by the utilization of energy saving technology, cogeneration plant. Cogeneration plant has potential of high economic and energy saving characteristics by energy efficient utilization. Different geographical locations have different climatic conditions in terms of average temperature and humidity. In the commercial sector, power demands peak in the summer daytime because of high space cooling demands, and cogeneration plants are required to produce maximum power to meet their demands. However, gas turbine with cogeneration plants have the disadvantage of decrease in maximum power output in the summer daytime, which reduces the availability of gas turbine.

Frank J. Brooks [2] presented the paper which reviewed the factors affecting the gas turbine performance. He reported that as the gas turbine is an air-breathing engine, its performance is changed by anything that affects the density and mass flow of the air intake to the compressor. Ambient weather conditions are the most obvious changes from the reference conditions. They carried out investigation that how ambient temperature affects the output, heat rate, heat consumption, and exhaust flow of a typical single-shaft gas turbine. Badran [3] studied the factors to improve the performance of the gas turbine. He observed that the thermal efficiency of the cycle improves as the inlet air-temperature decreases. Pankaj K. Patel [4] has developed a model of Earth Tube Heat Exchanger technology to reduce the inlet temperature of ambient air to the compressor inlet. He found that, this technology is not only eco-friendly but it is also economical both in terms of capital cost and running cost. Jaber et al. [5] proposed the use of the evaporative cooling system to boost the output power and to enhance the efficiency of the gas turbine unit. Basrawi [6] investigated the effect of ambient temperature on the performance of micro gas turbine with cogeneration. They observed that when ambient temperature increases, electrical efficiency of micro gas turbine decreases. Yokoyama and Ito [7] investigate the effect of inlet air cooling by ice storage on the unit sizing and cost of a gas turbine cogeneration plant. They numerically studied the gas turbine cogeneration plants with and without inlet air cooled by ice storage. They compared the effect of inlet air cooling on the equipment capacities with each other. Alhazmy and Najjar [8] analyzed the performance enhancement of gas turbine power plants by cooling the air at plant intake. A comparison between usage of two different types of air coolers, water spraying system and cooling coil, was performed. They found that the spray coolers ware capable of boosting the power and enhancing the efficiency of the gas turbine power plant much cheaper than the cooling coils. Bedecarrats and strub [9] made an attempt to enhance the gas turbine performance using an air cooler with a phase change energy storage. They reported that the inlet air cooling increases the performance of the installed turbine. Dawoud et al. [10] estimated the cooling capacities required for several inlet air cooling techniques for small size gas turbine power plants in two different locations using typical meteorological year data. Badran [11] studied the factors to improve the performance of the gas turbine. He observed that the thermal efficiency of the cycle improves as the inlet air temperature decreases. Arrieta and Lora [12] studied the influence of ambient temperature, atmospheric pressure and the air's relative humidity on combined cycle power plant performance. They observed these parameters affect the generated electric power and the heat rate during operation. They noticed among these variables, the ambient temperature causes the greatest performance variation during operation. Bassil [13] made an attempt to improve the efficiency and power of gas turbine using an absorption type inlet air cooling system. The influences of the intercooling on the gas turbine cycle are mapped and examined by Caniere et al. [14]. They raised the cycle efficiency by intercooling in air-cooled gas turbines. They noticed that intercooling not only lowers the work of compression, but also lowers cooling air temperatures. Johnson [15] presented a discussion of the theory and operation of evaporative coolers for industrial gas turbine installations. Calculations of parameters to predict the performance of evaporative cooler were included. Ondryas et al. [16] investigated using chillers at the air intake to boost gas turbines power in cogeneration plants during high ambient temperatures. Mercer [17] reported on different cooling techniques for the gas turbine inlet air. It is reported that chillers utilizing thermal storage systems increase the gas turbine output by 25% during peak cooling periods. Evaporative coolers, on the other hand, give an increase of 10–15% in the power output.

In the present study, for a further understanding of the effect of the ambient temperature, ambient pressure, relative humidity and inlet air temperature on the performance of gas turbine, an analysis based on 24 hours data has been carried out. The main objective is to determine the effect of variation in ambient air temperature on the performance of the gas turbine based cogeneration system.

Nomenclature

P_{atm}	Ambient pressure, mbar
T_{atm}	Ambient temperature, ^{0}C
R.H.	Relative humidity, %
m_s	Steam flow, t/h
m_f	Fuel gas flow, m^3/hr
r	Compressor pressure ratio
η_{th}	Thermal efficiency, %
η_o	Overall efficiency, %

II. TEST INSTRUMENTATION AND METHODOLOGY

A schematic diagram of cogeneration plant is shown in Figure 1. This plant consists of a gas turbine and heat recovery steam generator (HRSG). Figure 1 also depicts the instrumentation for the test. The ambient pressure, temperature and relative humidity are obtained from the laboratory at utility and environmental control department. Two thermocouples are situated in the compressor inlet duct to measure the inlet air temperature at compressor. The expected uncertainty of each sensor is +/-0.1 ^{0}C. The arithmetic average of thermocouples reading is indicated by the gas turbine control system (Speed Tronic Mark-IV) which is located in control room. Gas turbine output is also displayed through MW transducer by the gas turbine control system. The gas fuel flow is measured with the fuel flow meter. The accuracy of the orifice meter is 1% over the entire range of operation of the instrument. A pressure transmitter with uncertainty of 0.25% and a RTD with uncertainty of +/-0.1 ^{0}C are used for pressure and temperature measurement respectively. The gas fuel flow is indicated by Distributed Control Systems in the control room. Eighteen thermocouples (TTXD-1 to 18) are situated in the gas turbine exhaust plenum to measure the temperature of exhaust gas. The arithmetic average of thermocouples reading (TTXM) is indicated by the gas turbine control system. The data which are logged from gas turbine control system (Speed Tronic Mark-IV) and Distributed Control Systems are

- Gas turbine output
- Compressor inlet air temperature (CTIM)
- Compressor discharge air temperature (CTD)
- Compressor discharge pressure (CPD)
- Turbine exhaust gas temperature (TTXM)
- Gas turbine total firing hours
- Fuel gas flow
- Steam flow
- Steam temperature
- Steam pressure

All the instruments are calibrated regularly. Table 1 shows the technical specifications of the HRSG. Table 2 shows the basic specifications of the gas turbine.

Table 1, Technical specification of the HRSG

Make	: BHEL, Trichinapalli
Type	: Water tube, natural circulation
Steam drum	: Horizontal, single pressure
Source of heat	: Gas turbine exhausts
Steam generating capacity	: 75 t/hr (40.5 kg/cm^2, 355 ^{0}C), 125 t/hr (with supplementary firing)
Supplementary fuel	: Natural gas

Table 2, Basic specifications of the gas turbine

Make	: General Electric, USA
Model	: PG 6541 (B)
Type	: Frame type, single shaft, heavy duty
Fuel	: Natural gas
Output	: 38340 kW
Speed	: 5100 rpm
Heat rate	: 11460 kJ/KWhr (10860 Btu/kWhr)
Turbine inlet temperature	: 1104 ^{0}C
Exhaust flow	: 500500 kg/hr
Exhaust temperature	: 565 ^{0}C
Frequency	: 50 Hz
Compressor	: Axial flow type
Compressor stages	: 17
Turbine stages	: 3
Combustors	: 10, reverse flow type
Control system	: Speed Tronic Mark IV

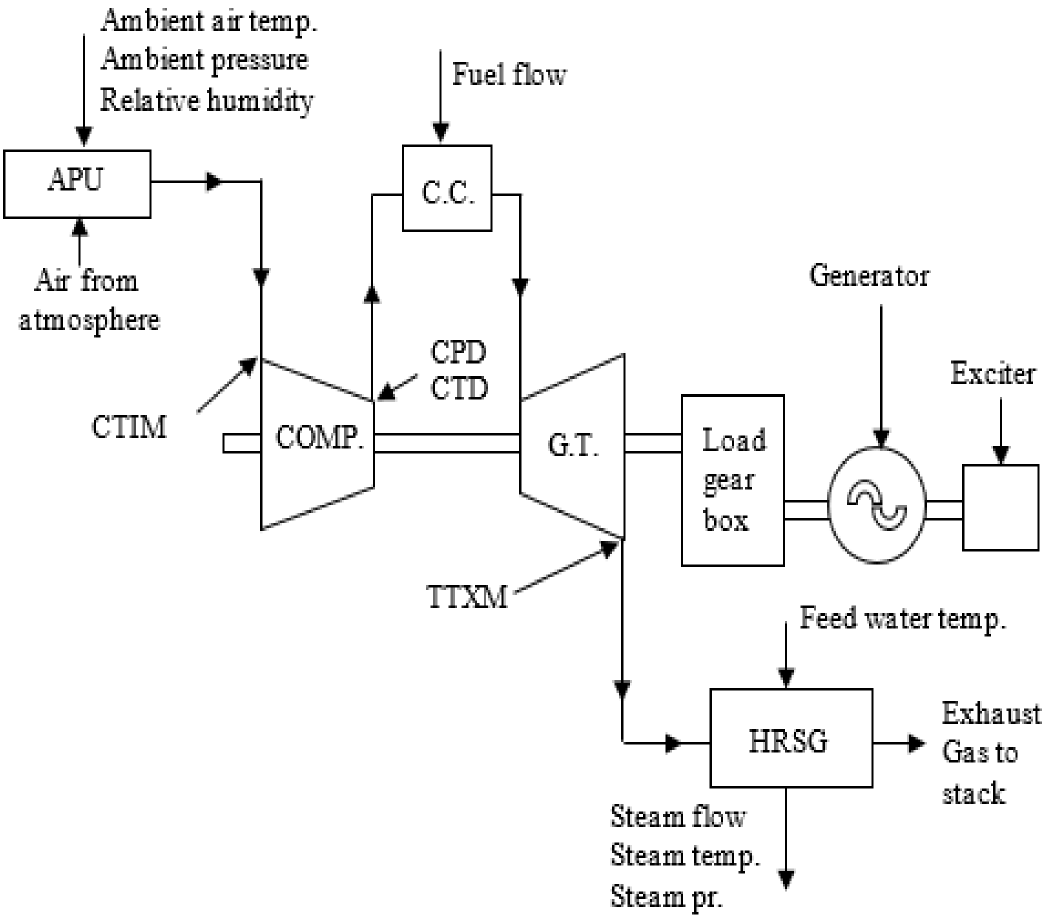

Figure 1. Schematic of instrumentation for the gas turbine based cogeneration system

Performance test of the gas turbine was conducted for the whole day. The gas turbine was operated in cogeneration cycle mode with HRSG. In a cogeneration plant, electric power is produced by the gas turbine and the heat energy of the exhaust gases is utilized to generate the process steam with the help of HRSG. The gas turbine was operated on the base load condition, i.e. full load of gas turbine. The test was carried out over a period of one day, from 8 a.m. to 7 a.m., i.e. for 24 hours in the month of March. The readings were taken at an interval of 1 hour. The experiment was conducted without supplementary firing in HRSG. Table 3 shows the values of the variables that were observed for the parametric study. Table 4 shows the results of thermal efficiency, overall efficiency and heat rate.

Table 3, Observation table of the performance test for the whole day

Sr. no	Time hr	GT output MW	Ambient pr. P_{atm} mbar	Ambient temp. T_{atm} °C	Relative humidity R.H. %	Comp. inlet temp. CTIM °C	Comp. outlet temp. CTD °C	Comp. outlet pr. CPD bar	Fuel gas flow m^3/hr	Exhaust gas temp. TTXM °C	Steam flow m_s t/h
1	8.00	30.38	1003	25.8	63	25	360	9.39	11100	561	65
2	9.00	29.28	1004	27.9	52	28	360	9.14	11000	565	64
3	10.00	29.11	1005	29.9	47	29	361	9.14	10950	565	63
4	11.00	28.76	1005	31.6	43	30	363	9.09	10700	565	61
5	12.00	28.18	1005	33.8	36	32	365	9.00	10600	565	61
6	13.00	27.77	1004	34.4	34	33	367	8.95	10600	565	61
7	14.00	27.37	1003	35.8	30	34	366	8.84	10550	565	60
8	15.00	26.85	1003	36.7	24	34	365	8.72	10400	565	59
9	16.00	26.89	1002	37.3	25	34	366	8.74	10400	565	60
10	17.00	27.27	1002	37.3	23	34	367	8.84	10400	564	61
11	18.00	27.60	1001	36.5	27	34	368	8.89	10450	565	61
12	19.00	27.71	1002	34.0	32	33	366	8.89	10500	565	62
13	20.00	28.58	1002	33.5	33	31	364	9.05	10600	565	61
14	21.00	29.33	1003	30.6	41	29	364	9.21	10700	564	62
15	22.00	30.05	1003	28.7	52	27	362	9.36	10900	562	63
16	23.00	29.91	1003	27.9	57	27	361	9.33	10900	563	63
17	0.00	29.99	1003	28.0	57	26	361	9.32	10950	562	62
18	1.00	29.72	1002	27.7	57	27	361	9.26	10950	563	63
19	2.00	30.51	1003	26.1	64	25	362	9.48	11100	560	63
20	3.00	30.50	1004	26.2	61	26	362	9.47	11100	560	63
21	4.00	30.13	1003	25.9	43	26	362	9.39	11050	561	64
22	5.00	30.38	1003	24.9	45	25	360	9.41	11100	561	64
23	6.00	30.51	1002	24.0	47	24	357	9.43	11200	561	65
24	7.00	30.73	1003	24.2	48	24	359	9.53	11250	560	65

Sample calculation for the reading no.1

Thermal efficiency (simple cycle efficiency):

$$\eta_{th} = \frac{W_{load} \times K}{LHV \times Q_{ft}} \times 100 \quad (1)$$

where,
W_{load} = 30380 kW, gas turbine output
K = 3600 kJ/kWhr
LHV = 35659 kJ/m^3, lower heating value of natural gas
Q_{ft} = 11100 m^3/hr, volume flow rate of fuel to the turbine

η_{th} = 27.63%

Overall system efficiency (cogeneration efficiency):

$$\eta_o = \frac{W_{load} \times K}{[LHV \times Q_{ft}] - [m_s (h_s - h_{fw})]} \times 100 \quad (2)$$

where,
W_{load} = 30380 kW, gas turbine output
K = 3600 kJ/kWhr
LHV = 35659 kJ/m^3, lower heating value of natural gas

Q_{ft} = 11100 $m^{3,}$ volume flow rate of natural gas
m_s = 65000 kg/hr, mass flow of steam from HRSG
h_s = 3100.7 kJ/kg, enthalpy of the sup. steam (at 37.16 bar, 354 ^{0}C)
h_{fw} = 146.6 kJ/kg, enthalpy of the feed water at 35^0 C

η_o = 53.66%

Heat rate:

$$Heat\ rate = \frac{Fuel\ consumption\ by\ GTG \times \text{LHV of fuel gas}}{Output\ power} \quad (3)$$

where,
$Fuel\ consumption\ by\ GTG$ =11100 m^3
$LHV\ of\ fuel\ gas$ = 35659 kJ/m^3
$Output\ power$ = 30380 kW

$Heat\ rate$ = 13029 kJ/kWhr (3112 kcal/kWhr)

Table 4, Computation table of the performance test for the whole day

Sr. no	Time	Ambient temp. T_{atm} ºC	Gas turbine output MW	Comp. pressure ratio r	Fuel gas flow m_f m^3/hr	Thermal efficiency η_{th} %	Overall efficiency η_o %	Heat rate kJ/kWhr	Heat rate kcal/kWhr
1	8.00	25.8	30.38	10.4	11100	27.63	53.66	13029	3112
2	9.00	27.9	29.28	10.1	11000	26.87	51.88	13396	3200
3	10.00	29.9	29.11	10.1	10950	26.84	51.28	13413	3204
4	11.00	31.6	28.76	10.0	10700	27.14	51.42	13267	3169
5	12.00	33.8	28.18	10.0	10600	26.84	51.29	13413	3204
6	13.00	34.4	27.77	9.9	10600	26.45	50.55	13611	3251
7	14.00	35.8	27.37	9.8	10550	26.19	49.52	13745	3283
8	15.00	36.7	26.85	9.7	10400	26.06	49.18	13812	3299
9	16.00	37.3	26.89	9.7	10400	26.10	50.00	13792	3294
10	17.00	37.3	27.27	9.8	10400	26.47	51.49	13599	3248
11	18.00	36.5	27.60	9.9	10450	26.66	51.63	13501	3225
12	19.00	34.0	27.71	9.9	10500	26.64	52.16	13512	3227
13	20.00	33.5	28.58	10.0	10600	27.22	52.02	13226	3159
14	21.00	30.6	29.33	10.2	10700	27.67	53.22	13009	3107
15	22.00	28.7	30.05	10.3	10900	27.83	53.40	12935	3089
16	23.00	27.9	29.91	10.3	10900	27.70	53.15	12995	3104
17	0.00	28.0	29.99	10.3	10950	27.65	52.08	13020	3110
18	1.00	27.7	29.72	10.2	10950	27.40	52.36	13138	3138
19	2.00	26.1	30.51	10.5	11100	27.75	52.38	12973	3098
20	3.00	26.2	30.50	10.4	11100	27.74	52.36	12978	3099
21	4.00	25.9	30.13	10.4	11050	27.53	52.92	13078	3123
22	5.00	24.9	30.38	10.4	11100	27.63	52.90	13029	3112
23	6.00	24.0	30.51	10.4	11200	27.50	52.97	13090	3126
24	7.00	24.2	30.73	10.5	11250	27.58	52.89	13054	3118

III. RESULTS AND DISCUSSIONS

Referring to the results shown in Table 4, it can be observed that the maximum gas turbine output is 30.73 MW, while the minimum gas turbine output is 26.85 MW. It can be also noticed that the overall gas turbine output variation is 4 MW corresponding to overall temperature variation of 13 ^{0}C. Figure 2 shows the variation of ambient air temperature for the whole day. It can be observed that the maximum ambient temperature is found 37.3 ^{0}C in the afternoon while minimum ambient temperature is found 24 ^{0}C in the morning.

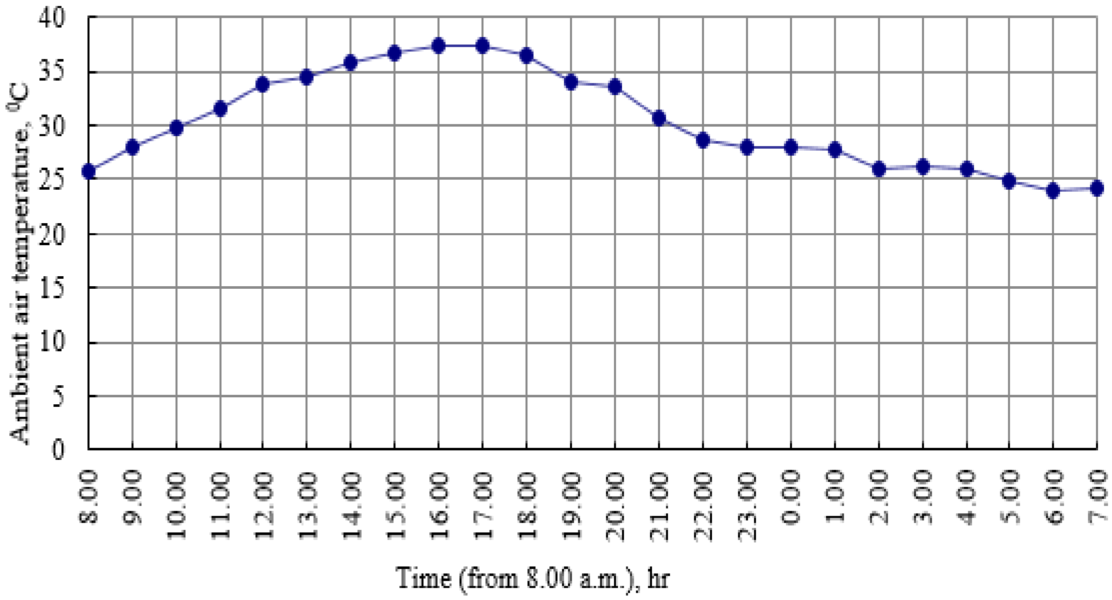

Figure 2, Variation of ambient air temperature for the whole day

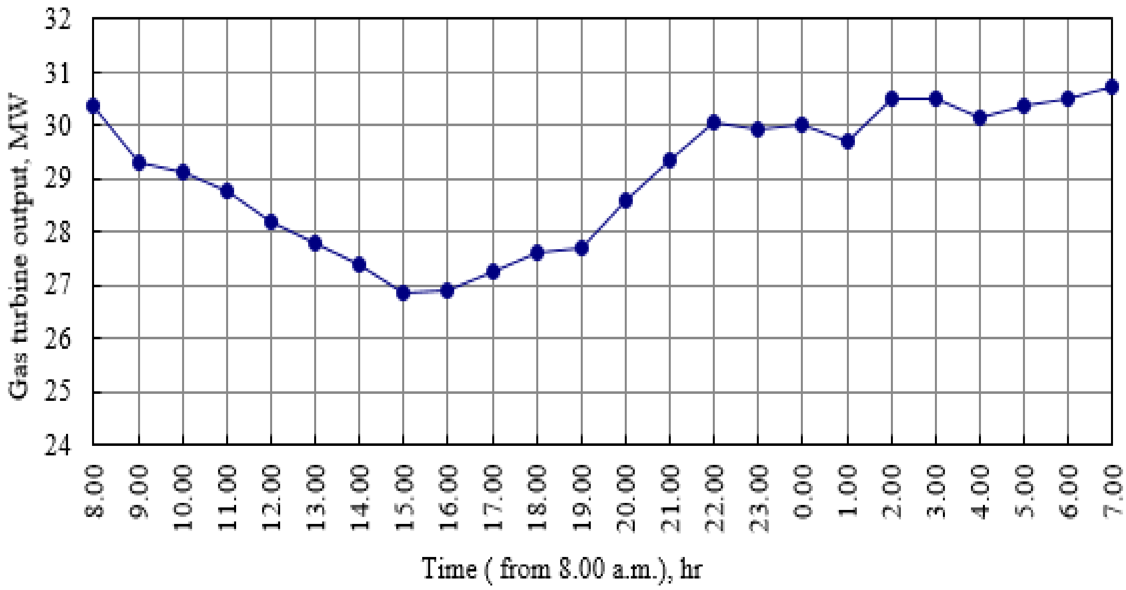

Figure 3, Variation of gas turbine output power for the whole day

Figure 3 depicts the variation of gas turbine output power for the whole day. It can be found that the maximum power output of 30.73 MW is observed at 7.00 a.m. (early morning) when ambient temperature is recorded 24.2 ^{0}C, while the minimum power output of 26.85 MW is observed at 15.00 p.m. (noon) when ambient temperature is recorded 36.7 ^{0}C. The performance of the gas turbine is greatly depends on inlet air temperature to the compressor. The gas turbines are constant volume machines. The volume of the compressed air is fixed, irrespective of the ambient temperature. As the temperature of air increases, the density of air decreases hence, the mass flow rate of the compressed air gets reduced. The gas turbine output is proportional to the mass flow rate of compressed air. Therefore, the gas turbine output decreases with decreased air flow rate. It is found that the gas turbine power output decreases with increasing ambient temperature. Further, the efficiency of the gas turbine also falls, as more power requires to compress the warm air. From the equation (1), if gas turbine output decreases than thermal efficiency reduces. This can be observed from Figure 4 that the thermal efficiency is marginally decreased at noon. The reduction in power output due to increasing ambient temperature has similar effect on the overall efficiency. From the equation (2), as gas turbine output decreases, the overall efficiency decreases. This can be noticed from the Figure 5, that overall efficiency decreases at noon due to increase in ambient temperature. The decrease in output power has inverse effect on the heat rate. From the equation (3), as gas turbine output decreases, the heat rate increases. The heat rate is inversely proportional to the gas turbine power output.

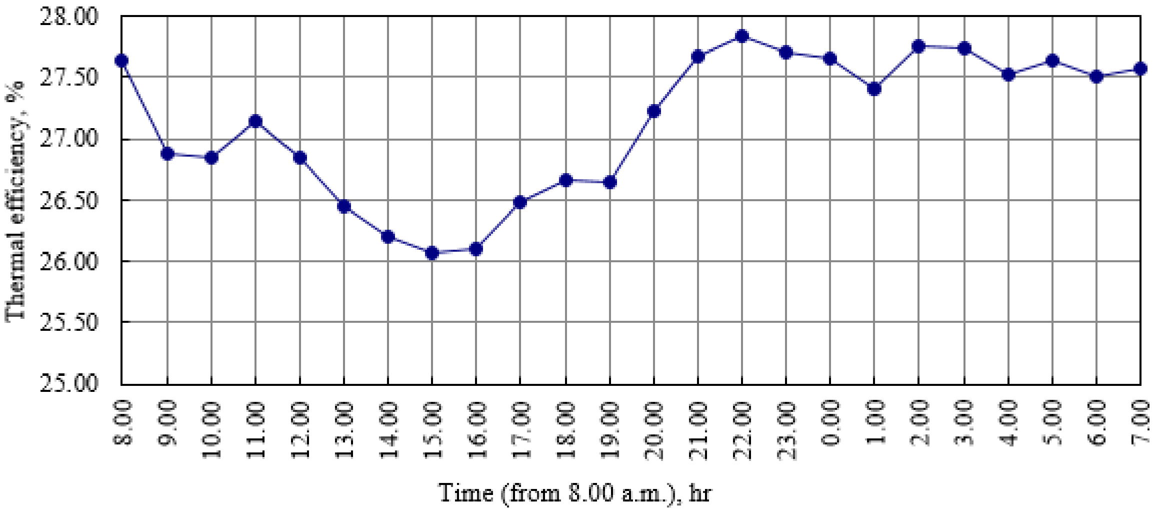

Figure 4, Variation of thermal (simple cycle) efficiency for the whole day

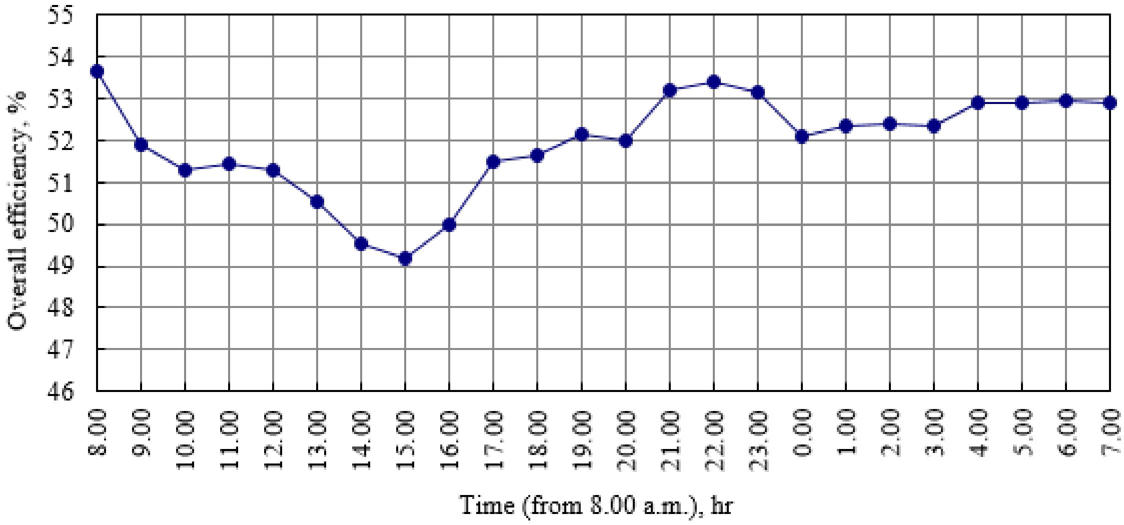

Figure 5, Variation of overall (cogeneration) efficiency for the whole day

Figure 6 depicts that the heat rate increases at noon due to increase in ambient temperature. It was observed that the maximum heat rate of 3299 kcal/kWhr is required at 15.00 p.m. (noon) when the ambient temperature is recorded 36.7 ^{0}C. It can be concluded that on hot days, when air is less dense, power output falls off. A rise in temperature of inlet air decreases the power output and at the same time increases the heat rate of the turbine. This is a matter of great concern to power producers.

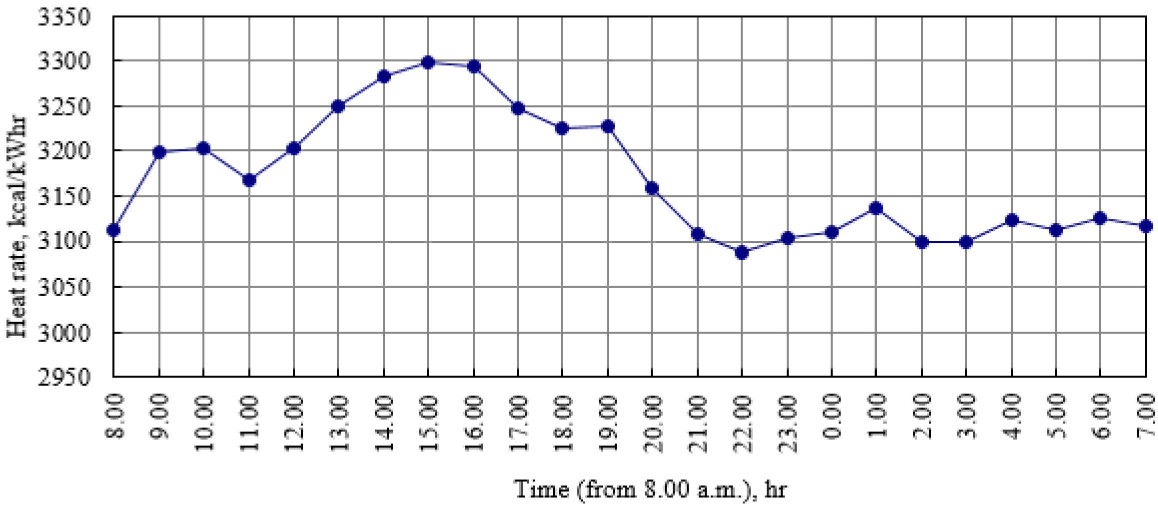

Figure 6, Variation of heat rate for the whole day

IV. CONCLUSIONS

The Performance assessment of the gas turbine is essential for the efficient utilization of turbo machinery in cogeneration system. The whole day performance of the gas turbine in cogeneration plant has given some insight into the influence of changes in ambient temperature on the gas turbine output power and heat rate. Following conclusions are drawn from the present work.

- The gas turbine is an air-breathing engine. The performance of the gas turbine directly depends on ambient and operating conditions. Its performance is influenced by anything that affects the density and mass flow rate of the air intake to the compressor. It is not only affected by site elevation but also by the changes in ambient temperature and relative humidity.
- Changes in ambient temperature have significant impact on the gas turbine power output and the heat rate. A rise in temperature of ambient air decreases the power output and at the same time increases the heat rate of the turbine. It was observed that the maximum output of 30.73 MW is produced at 7.00 a.m. (early morning) when ambient temperature is recorded 24.2 ^{0}C, while the minimum output of 26.85 MW is produced at 15.00 p.m. (noon) when ambient temperature is recorded 36.7 ^{0}C. It was also noticed that the overall gas turbine output variation was 4 MW corresponding to overall temperature variation of 13 ^{0}C.The air density changes due to change in the ambient air temperature. Increased ambient temperature lowers the density of the inlet air, which results in reduced mass flow through the turbine and therefore, reduces the power output.
- Increased ambient temperature reduces the power output, therefore increases the heat rate. It was observed that the maximum heat rate of 3299 kcal/kWhr is required at 15.00 p.m. (noon) when ambient temperature is recorded 36.7 ^{0}C. Heat rate is inversely proportional to the power output.

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