IMPACT OF INLET FOGGING AND FUELS ON POWER AND EFFICIENCY OF GAS TURBINE PLANTS

by

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A computational study to assess the performance of different gas turbine power plant configurations is presented in this paper. The work includes the effect of humidity, ambient inlet air temperature and types of fuels on gas turbine plant configurations with and without fogger unit. Investigation also covers economic analysis and effect of fuels on emissions. Gas turbine frames of various sizes/ratings are being used in gas turbine power plants in Saudi Arabia. 20 MW_e GE 5271RA, 40 MW_e GE-6561B, and 70 MW_e GE-6101FA frames are selected for the present study. Fogger units with maximum mass flow rate of 2 kg/s are considered for the present analysis. Reverse osmosis unit of capacity 4 kg/s supplies required water to the fogger units. The relative humidity and temperature have been varied from 30 to 45% and from 80 to 100 °F, respectively. Fuels considered in the study are natural gas, diesel and heavy bunker oil. Simulated gas turbine plant output from Gas turbine PRO has been validated against an existing gas turbine plant output. It has been observed that the simulated plant output is less than the existing gas turbine plant output by 5%. Variation of humidity does not affect the gas turbine performance appreciably for all types of fuels. For a decrease of inlet air temperature by 10 °F, net plant output and efficiency have been found to increase by 5 and 2%, respectively, for all fuels, for gas turbine only situation. However, for gas turbine with fogger scenario, for a decrease of inlet air temperature by 10 °F, net plant output and efficiency have been found to further increase by 3.2 and 1.2%, respectively for all fuels. For all Gas turbine frames with fogger, the net plant output and efficiency are relatively higher as compared to gas turbine only case for all fuels. Net plant output and efficiency for natural gas are higher as compare to other fuels for all gas turbine scenarios. For a given 70 MW_e frame with and without fogger, break even fuel price and electricity price have been found to vary from 2.2 to 2.5 USD/MMBTU and from 0.020 to 0.0239 USD/kWh, respectively. Turbines operating on natural gas emit less carbon relatively as compared to other fuels.

Keywords *inlet fogging, plant efficiency and output, gas turbines, fuels, break even fuel, electricity price*

Introduction

Gas turbines (GT) are widely used for power generation globally. In hot and dry air climates, such as gulf countries including Saudi Arabia, gas turbine engine power output is dramatically reduced because of the reduction in gas turbine air mass flow due to high ambient inlet air temperature. Cooling the inlet air to the wet bulb temperature will increase the density of the air and air mass flow, and hence will boost the power and efficiency of the plant. Different available

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cooling technologies for cooling inlet air are fogging, chilling, evaporative cooling, *etc*. However, in recent past, inlet fogging technology is being employed world-wide to reduce the inlet ambient air temperature [1-3]. Also, considerable amount of research is been carried out on gas turbines (impact of fuels, impact of fogging, *etc*.) worldwide [4-15].

The initial discussion on inlet fogging of gas turbine was made by Chaker *et al*. [1, 2]. Fog inter cooling which has been applied from the early days of gas turbine and jet engine technology is a technique that consists of spraying more fog than that will evaporate under the given ambient temperature and humidity conditions so that non-evaporated liquid water droplets enter the compressor. The desired quantum of un-evaporated fog is carried with the air stream into the compressor, where it evaporates and produces an inter-cooling effect. The resulting reduction in the work of compression can give a significant additional power boost [1, 2].

Fogging systems spray atomized water into the GT inlet air. Evaporative cooling system consists of moistened media through which the GT inlet airflow passes, to cool down by evaporation. Chiller system is similar to air-condition chiller used to cool large buildings. In this system, chilled water is circulated through a finned-tube coil placed in the GT inlet air path. This cools down the inlet air, possibly condensing some of its moisture, which is drained away [9]. Present study focuses on inlet fogging due to its merits in hot climatic conditions (has been qualitative argued in the results and discussion section).

Amount of water sprayed in inlet air stream defines the type of inlet fogging, namely under spray and over spray [10, 11]. In under spray, air is cooled by evaporating fog, without droplets entering the compressor. However, in over spray, excessive water droplets enter the compressor and will affect its performance. Furthermore, certain gas turbine engines are unsuitable to overspray fogging, and some manufacturers do not recommend overspray for GT [9].

Chaker *et al.* [3], performed experimental and theoretical studies on impaction pin fog nozzle used for gas turbine inlet fogging and the dynamics of inlet fogging in general. It has been shown that ambient humidity levels do not significantly affect droplet size. Sanjeev Jolly [4] has presented the thermodynamic benefits of wet compression and performance results of the system application on a GE frame 6B combustion turbine in which the power output is augmented by 9%. Wet compression is a process in which water droplets are injected into the compressed inlet air and allowed to be carried into the compressor. As the water droplets evaporate in the front stages of the compressor, it reduces the air temperature and therefore reduces the amount of work that must be done by the compressor air foils to pass the flow on to the next stage of compressor blade. The net effect is reduction in compressor work [4].

A review of the basic principles and practical aspects of fogging technology can be found in Meher-Homji and Mee [5, 6]. Bhargava *et al*. [7] have presented a comprehensive review on the current understanding, analytical, experimental and field experience of the high-pressure inlet fogging technology for gas turbine applications. The study also highlights that ambient temperature strongly influences the gas turbine performance with power output dropping by 0.5 to 0.9% for every 1 °C rise in temperature. A brief discussion on the status of development in the area of fogging by major gas turbine manufacturers has also been presented.

Nishino *et al.* [8] investigated optimal operational strategy for an existing gas turbine co-generation plant with steam injection and inlet air cooling. The investigation was carried out for various power demands and ambient air conditions. It has been found that adoption of inlet air cooling is effective for the cases with various demands under high temperature or low humidity of the ambient air. Literature indicates that type of fuels used in GT plants influences performance and efficiency of the plant [12-15].

The present work involves assessment of performance of gas turbine power plants with and without inlet fogging. The study has been carried out for a given location, Riyadh (for 20 MW_e GE 5271RA, 40 MW_e GE-6561B, and 70 MW_e GE-6110A frames and fogger units with required mass flow rate) using GT PRO software based on available data/information. Reverse osmosis unit of capacity 4 kg/s supplies required water to the fogger unit. GT PRO is a popular software for designing gas turbine power plants. GT PRO is used to calculate heat balance and cost estimate of the power plant [9]. The study involves effect of variation of fuels, relative humidity (RH) and inlet air temperature on gas turbine performance for different GT frames. Also, this software has been used to analyze net plant output, net efficiency, break even electricity price (BEEP) and break even fuel LHV price (BEFP), carbon emissions, *etc*. Simulations have been made for different scenarios such as gas turbine performance evaluation with and without inlet fogging.

Methodology

Gas turbines are constant volume machines. At a given shaft speed they always move the same volume of air, but their power output depends on the mass flow through the turbine. During hot days, when the air is less dense, power output drops. By cooling the air, mass flow is increased, thus increasing the power output. Also, about 30-40% of the power produced by the turbine is needed to drive the compressor. If the air is cold, the power required by the compressor is less, leaving more power available for the turbine output shaft. Fogging technique is widely used to reduce the inlet air temperature of compressor. Fogging system sprays atomized water into the GT inlet air. The fog is generated by forcing water at high pressures (100 ~200 bar) through minute holes in arrays of nozzles, arranged across the GT inlet ducting. As per recommendation in the literature, underspray fogging has been used in the present study [10]. Unclean and saline water will clog the nozzles. Clogging can be avoided by regular maintenance and using desalinated water for fogging. Reverse osmosis unit is used to provide desalinated water to the fogging unit. System configuration simulated in the present study is shown in fig. 1. Fogging unit injects atomized water at the entrance of the inlet duct before the filters as depicted in fig. 1. Typical gas turbine performance curves are shown in fig. 2. It can be seen that as ambient

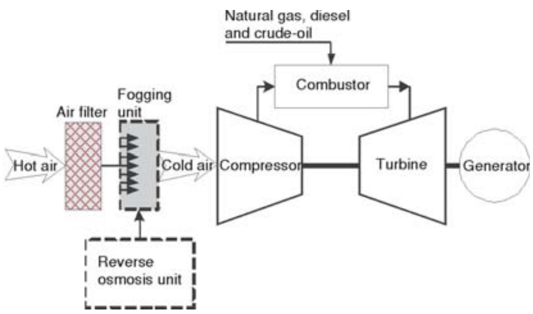

Figure 1. Gas turbine configuration used in the study

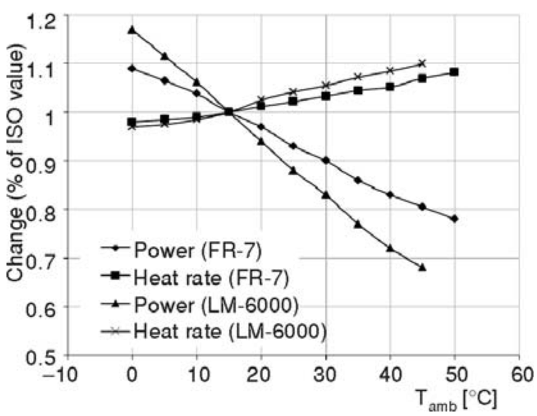

Figure 2. Effects of ambient temperature on the performance of gas turbine [11]

temperature decreases power output and air flow increase. Whereas, heat rate and exhaust gas temperature increase with increase in ambient temperature.

Commonly used GT frames in Saudi Arabia are listed in tab. 1. Gas Turbine inputs and plant criteria such as fuel type, ambient temperature, ambient pressures and RH *etc*. are assumed in accordance with the site location. Assumed project life, operation hours per year and load factor are 20 year, 6132 (is 70% of the total hours per year, assuming 30% for maintenance/outages activities) and 100%, respectively. Study assumptions used in simulations are listed in tab. 2. Fogger efficiency in the present study is assumed to be 85%. This means fogger unit brings down the inlet air temperature close to 85% of wet bulb temperature.

Table 1. Specifications of commonly used gas turbines in Saudi Arabia

Manufacturer	Site rating [MW_e]	Name plate rating [MW_e]	Full load heat rate BTU/kWh	Fuel type
Westinghouse	67.0	92.7	14,605	gas
General Electric	60	74.4	12,190	gas
Mitsubishi	46.9	63.9	16,200	gas
Westinghouse	24.0	56	16,980	gas
Fiat	19.1	31.5	17,714	gas
Fiat	27.5	30	13,865	crude-oil
General Electric	29	33	12,190	diesel

Table 2. Study assumptions

Parameter	Detail
Air filter pressure drop	0.144 PSI
Fuel heating	No
Fuel compression	No
Steam injection	No
Fuels	Natural gas (LHV: 20,267 BTU/lb.), Diesel (LHV: 18,320 BTU/lb.) & Bunker oil (LHV: 18,352 BTU/lb.)
Fogger efficiency	85%
Pressure drop of air stream due to fogging	1"
GT power as % of site rating	100
Operating hours per year (full-load equivalent)	6132
First-year fuel LHV price (USD/MMBTU)	0.78
First-year electricity price (USD/kWh)	0.04

In order to simulate a given GT plant for a given location (using GT PRO), input information to be provided includes: site specific conditions, size and type of GT frame, type of fuel, fuel characteristics, pressure drops in the system, GT inlet air temperature, fogger efficiency, load factor, fuel LHV buying price, electricity selling price, *etc*. Using the above data, simulations are performed for different inlet air temperatures (80 to 100 °F, RH 30-45%) with and without fogging and the results of simulations include (but not limited to): plant net output, net plant efficiency, heat rate, break even electricity price, break even fuel price, emissions, *etc*.

Results and discussions

In order to carry out the present study, General Electric GT frames with rated capacities of 20 MW_e GE 5271RA, 40 MW_e GE-6561B, and 70 MW_e GE-6110A and fogger units with required mass flow rate have been selected. Several simulations were made for different scenarios such as gas turbine performance evaluation with and without inlet fogging using GT PRO software. This software has been used to analyze net plant output, net efficiency, BEEP and BEFP, carbon emissions, *etc*. The study involves effect of variation of fuels, RH and ambient inlet air temperature on gas turbine performance for different GT frames. For the sake of brevity, simulation results obtained from 70 MW_e GT frame are presented.

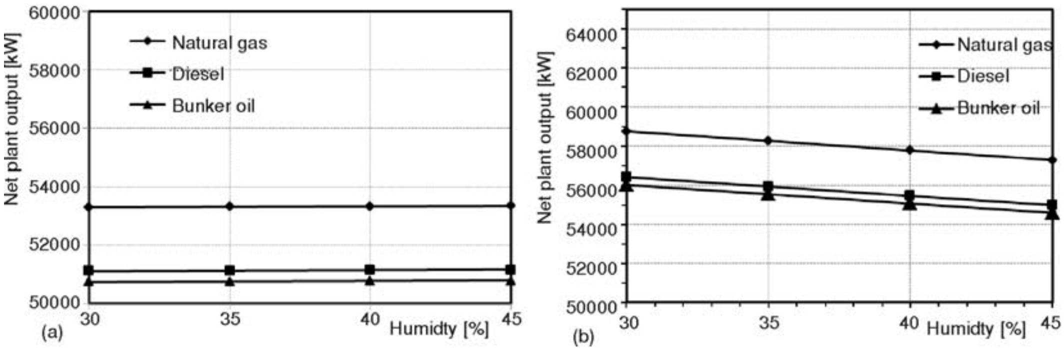

Figure 3. Effect of humidity on net plant output for a given GT frame GE 70, temperature 100 °F, for all fuels; (a) GT only, (b) GT with fogger unit

The effect of humidity on net plant output (for a given inlet air temperature 100 °F, for all fuels) is shown in fig. 3. RH has been varied between 30- 45% (this covers the prevailing average RH range in Saudi Arabia). It can be noticed that variation of RH does not affect/improve the performance appreciably for GT only configuration. This observation is in agreement with an earlier study [3]. However, variation of RH has little effect on net plant output. For GT with fogger situation, introduction of fogger unit, variation of humidity has mild effect on performance. Due to presence extra moisture, "due to density variation" compressive work decreases (turbine output increases) and hence variation in performance is observed. For an increase in RH from 30 to 45%, net plant output has been found decrease by 2% for all fuels. Since, RH does not have much effect on the GT plant performance; it has been fixed at 30% in the present study.

The effect of ambient inlet air temperature on plant net output and efficiency (for a given RH of 30%, different fuels, 70 MW_e GT frame, with and without fogging) is shown in figs. 4 and 5. It can be noticed that variation of ambient inlet air temperature has significant effect on the plant net output and efficiency regardless of type of fuel. The plant net output and efficiency increase with decrease in ambient inlet air temperature. This can be attributed to the fact that with decrease in ambient inlet air temperature, air density and air mass flow increase (which eventually results in high power output). This indicates that plant net output and efficiency strongly depend on ambient temperature.

For GT only situation, for a decrease of ambient inlet air temperature by 10 °F, plant net output has been found to increase by 4.6% for all fuels. Also, for a decrease of ambient inlet air temperature by 10 °F, plant net efficiency has been found to increase by 1.8% for all fuels. The increment may grow further for bigger GT frames. This observation is in good agreement

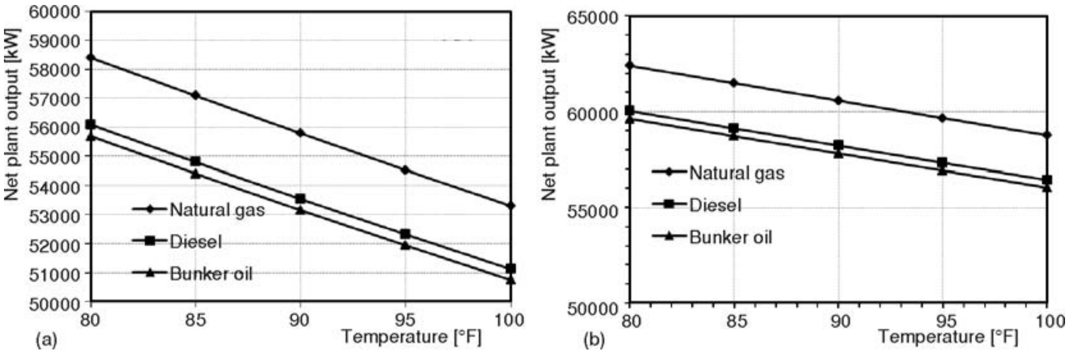

Figure 4. Effect of temperature on net plant output for a given GT frame GE 70, temperature 100 °F, for all fuels; (a) GT only, (b) GT with fogger unit

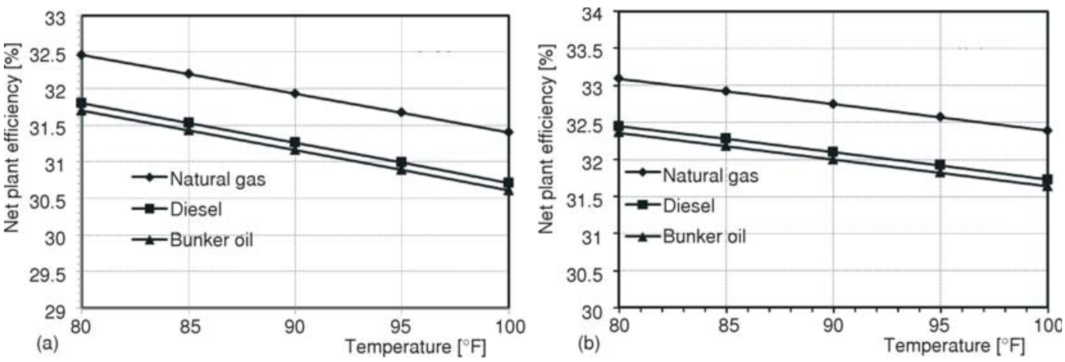

Figure 5. Effect of temperature on net plant efficiency for a given GT frame GE 70, temperature 100 °F, for all fuels ; (a) GT only, (b) GT with fogger unit

with the findings of other research studies [7]. While, for GT with fogger situation, for a decrease of ambient inlet air temperature by 10 °F, plant net output has been found to further increase by 3.2% for all fuels as compared to GT only situation. Also, for a decrease of ambient inlet air temperature by 10 °F, plant net efficiency has been found to further increase by 1.2% for all fuels as compared to GT only situation. For GT only case, 70 MW_e frame the mass flow rate of air varies from 350 to 330 lb/s.

For GT only situation, observation shows that, for natural gas, net plant output and efficiency are higher than diesel and bunker oil by 4-5% and 2-3%, respectively, regardless of operating temperature. While, similar observations has been noticed for GT with fogger situation.

Ambient inlet air temperature not only has impact on plant net output and efficiency but also affects plant economics, namely, BEFP and BEEP. BEFP refers to the maximum price at which fuel can be purchased from the local market. For instance, if the fuel is bought at a price higher than the BEFP then the economics of the power plant will be affected. On the contrary, BEEP refers to the minimum price at which electricity can be sold to the market. If electricity selling price is less than the BEEP then the economics of the power plant will be affected.

The effect of ambient inlet air temperature on BEFP for GT with and without fogger situation (for given humidity of 30%, for all fuels, 70 MW GT frame) is shown in fig. 6. It can be

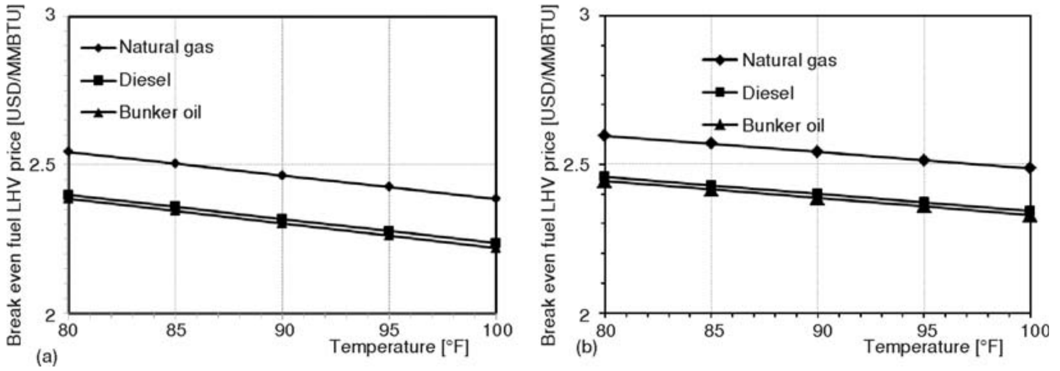

Figure 6. Effect of temperature on break even fuel price for a given GT frame GE 70, temperature 100 °F, for all fuels; (a) GT only, (b) GT with fogger unit

noticed that regardless of GT configuration and type of fuel, BEFP increases with decrease in inlet air temperature. It can also be observed that the BEFP of natural gas is higher than the BEFP of other fuels. This can be attributed to higher performance and efficiency of turbines working with natural gas.

For GT only situation (for 100 °F ambient inlet air temperature), BEFP are 2.385, 2.237, and 2.22 USD/MMBTU for natural gas, diesel and bunker oil, respectively. However, for GT with fogger situation (for 100 °F ambient inlet air temperature), BEFP are 2.486, and 2.343, 2.329 USD/MMBTU for natural gas, diesel and bunker oil, respectively.

The effect of ambient inlet air temperature on BEEP for GT with and without fogger situation (for given RH of 30 %, for all fuels, 70 MW GT frame) is shown in fig. 7. It can be noticed that regardless of GT configuration and type of fuel, BEEP decreases with decrease in inlet air temperature. It can also be observed that the BEEP of natural gas is lower than the BEEP of other fuels. Again, this can be attributed to higher performance and efficiency of turbines working with natural gas.

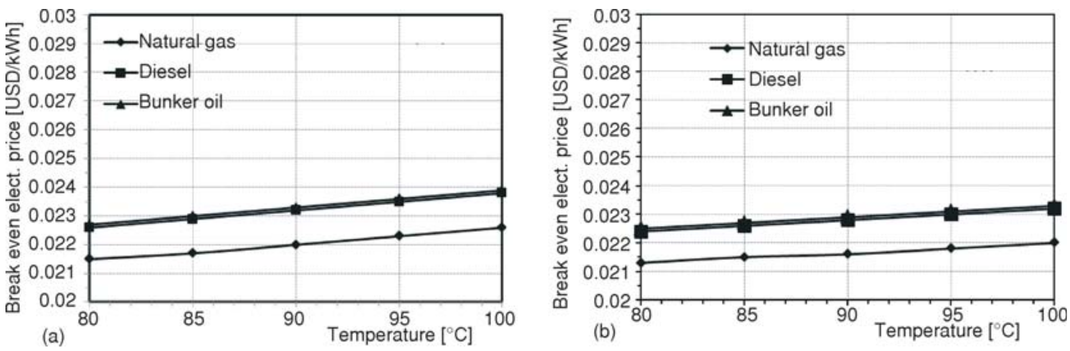

Figure 7. Effect of temperature on break even electricity price for a given GT frame GE 70, temperature 100 °F, for all fuels; (a) GT only, (b) GT with fogger unit

For GT only situation (for 100° F ambient inlet air temperature), BEEP are 0.0226, 0.0238, 0.0239 USD/kWh for natural gas, diesel and bunker oil, respectively. However, for GT with fogger situation (for 100 °F ambient inlet air temperature), BEEP are 0.0220, 0.0232, and 0.0233 USD/MMBTU for natural gas, diesel, and bunker oil, respectively.

The effect of ambient inlet air temperature on carbon emission for GT with and without fogger situation (for given RH of 30 %, for all fuels, 70 MW GT frame) is shown in fig. 8. It can be observed that regardless of GT configuration, carbon emissions increase with decrease in ambient inlet air temperature. However, for natural gas carbon emissions are relatively less as compared to other fuels.

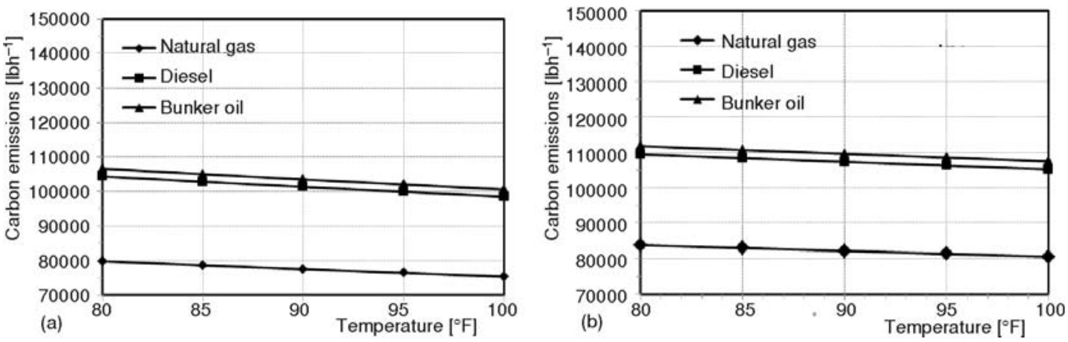

Figure 8. Effect of fuels on plant emissions for a given GT frame GE 70, temperature 100 °F, for all fuels; (a) GT only, (b) GT with fogger unit

As mentioned earlier, above discussion has been focused on 70 WM GT frame. The simulations results for 20 MW_e and 40 MW_e GT frames are tabulated in tabs. 3-5.

Conclusions

A computational study to assess the performance of different gas turbine plant configurations is presented. The work includes the effect of RH, ambient inlet air temperature, and types of fuels on gas turbine plant with and without fogger unit. It has been found that variation of RH does not affect the gas turbine performance appreciably for all types of fuels. For a decrease of inlet air temperature by 10 °F, plant net output and efficiency have been found to increase by 4.2 and 1.8 %, respectively, for all fuels, for GT only situation. However, for GT with fogger scenario, for a decrease of inlet air temperature by 10 °F, plant net output and efficiency have been found to further increase by 3.2 and 1.2%, respectively for all fuels. For all GT frames with fogger, the plant net output and efficiency are relatively higher as compared to GT only case for all fuels. More specifically, plant net output and efficiency for natural gas are higher as compared to other fuels for all GT scenarios.

For the study conditions (70 MW_e frame with and without fogger), BEFP and BEEP have been found to vary from 2.2 to 2.5 USD/MMBTU and from 0.020 to 0.0239 USD/kWh, respectively. It has also been observed that regardless of GT configuration, carbon emissions increase with decrease in ambient inlet air temperature. However, for natural gas carbon emissions are relatively less as compared to other fuels.

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Acronyms

BEEP – break even electricity price
BEFP – break even fuel price
GE – general electric
GT – gas turbine
LHV – low heating value
RH – relative humidity

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Table 3. Simulation results of different GT frames at different temperatures for a given RH = 30% and for natural gas fuel

Parameters		20 MW GE 5271RA					40 MW GE 6561B					70 MW GE 6101FA				
		80 °F	85 °F	90 °F	95 °F	100 °F	80 °F	85 °F	90 °F	95 °F	100 °F	80 °F	85 °F	90 °F	95 °F	100 °F
Net plant output [kW]	GT only	16536	16215	15897	15582	15269	33451	32774	32102	31449	30814	58396	57084	55787	54528	53305
	GT with fogger	17569	17288	17036	16784	16536	35629	35108	34605	34100	33600	62397	61484	60569	59656	58754
Net plant efficiency [%]	GT only	24.92	24.73	24.54	24.33	24.12	30.86	30.68	30.5	30.32	30.13	32.46	32.2	31.93	31.67	31.4
	GT with fogger	25.35	25.17	25.02	24.86	24.7	31.27	31.14	31.01	30.87	30.74	33.09	32.92	32.75	32.57	32.39
Break even fuel price [USD/ MMBTU]	GT only	1.606	1.574	1.544	1.511	1.478	2.303	2.272	2.24	2.209	2.177	2.543	2.504	2.464	2.425	2.385
	GT with fogger	1.599	1.568	1.543	1.516	1.489	2.32	2.295	2.271	2.246	2.221	2.596	2.569	2.542	2.514	2.486
Break even electricity price [USD/kWh]	GT only	0.0287	0.029	0.0294	0.0297	0.0301	0.0232	0.0234	0.0237	0.0239	0.0242	0.0215	0.0217	0.022	0.0223	0.0226
	GT with fogger	0.029	0.0293	0.0296	0.0299	0.0302	0.0232	0.0234	0.0236	0.0238	0.024	0.0213	0.0215	0.0216	0.0218	0.022
Total plant emissions [lb/h]	GT only	29473	29123	28780	28444	28115	48153	47447	46749	46075	45422	79911	78746	77597	76486	75411
	GT with fogger	30782	30512	30247	29987	29734	50603	50088	49574	49060	48552	83752	82953	82150	81352	80567

Table 4. Simulation results of different GT frames at different temperatures for a given RH = 30% and for diesel fuel

Parameters		20 MW GE 5271RA					40 MW GE 6561B					70 MW GE 6101FA				
		80 °F	85 °F	90 °F	95 °F	100 °F	80 °F	85 °F	90 °F	95 °F	100 °F	80 °F	85 °F	90 °F	95 °F	100 °F
Net plant output [kW]	GT only	16034	15718	15405	15094	14786	32432	31765	31104	30473	29848	56085	54799	53536	52321	51121
	GT with fogger	17046	16770	16521	16274	16029	34571	34066	33566	33070	32577	60020	59115	58213	57318	56436
Net plant efficiency [%]	GT only	24.5	24.31	24.11	23.9	23.69	30.39	30.21	30.03	29.84	29.65	31.8	31.53	31.26	30.99	30.71
	GT with fogger	24.94	24.75	24.6	24.44	24.28	30.82	30.68	30.55	30.42	30.28	32.45	32.28	32.1	31.92	31.73
Break even fuel price (USD/ MMBTU)	GT only	1.468	1.435	1.406	1.372	1.338	2.174	2.141	2.107	2.074	2.04	2.399	2.359	2.317	2.278	2.237
	GT with fogger	1.465	1.433	1.406	1.378	1.351	2.191	2.165	2.14	2.114	2.088	2.458	2.429	2.401	2.372	2.343
Break even electricity price [USD/kWh]	GT only	0.0304	0.0308	0.0311	0.0316	0.032	0.0244	0.0246	0.0249	0.0252	0.0255	0.0226	0.0229	0.0232	0.0235	0.0238
	GT with fogger	0.0306	0.031	0.0313	0.0317	0.032	0.0244	0.0246	0.0248	0.025	0.0253	0.0224	0.0226	0.0228	0.023	0.0232
Total plant emissions [lb/h]	GT only	38731	38270	37819	37377	36944	63153	62222	61303	60432	59573	104386	102857	101356	99923	98509
	GT with fogger	40451	40096	39748	39407	39074	66391	65710	65025	64347	63677	109456	108390	107329	106281	105248

Table 5. Simulation results of different GT frames at different temperatures for a given RH = 30% and for bunker oil

Parameters		20 MW GE 5271RA					40 MW GE 6561B					70 MW GE 6101FA				
		80 °F	85 °F	90 °F	95 °F	100 °F	80 °F	85 °F	90 °F	95 °F	100 °F	80 °F	85 °F	90 °F	95 °F	100 °F
Net plant output [kW]	GT only	15944	15629	15317	15007	14700	32263	31598	30941	30312	29688	55689	54407	53152	51942	50746
	GT with fogger	16952	16676	16428	16182	15938	34396	33892	33395	32899	32407	59611	58707	57808	56918	56037
Net plant efficiency [%]	GT only	24.44	24.24	24.04	23.84	23.62	30.33	30.15	29.97	29.78	29.59	31.7	31.43	31.16	30.89	30.61
	GT with fogger	24.88	24.69	24.54	24.38	24.22	30.76	30.62	30.49	30.35	30.22	32.36	32.18	32	31.82	31.64
Break even fuel price [USD/ MMBTU]	GT only	1.458	1.425	1.392	1.359	1.324	2.16	2.127	2.093	2.064	2.03	2.386	2.345	2.303	2.262	2.22
	GT with fogger	1.456	1.423	1.396	1.368	1.341	2.182	2.155	2.131	2.104	2.078	2.444	2.416	2.387	2.359	2.329
Break even electricity price [USD/kWh]	GT only	0.0305	0.0309	0.0313	0.0317	0.0321	0.0245	0.0248	0.025	0.0253	0.0256	0.0227	0.023	0.0233	0.0236	0.0239
	GT with fogger	0.0307	0.0311	0.0314	0.0318	0.0321	0.0244	0.0247	0.0249	0.0251	0.0253	0.0225	0.0227	0.0229	0.0231	0.0233
Total plant emissions [lb/h]	GT only	39590	39119	38657	38205	37763	64550	63597	62660	61769	60890	106606	105042	103513	102047	100601
	GT with fogger	41348	40985	40630	40281	39940	67863	67166	66465	65771	65085	111792	110699	109614	108542	107487