V94.2 Gas Turbine Thermodynamic Modeling for Estimation of Power Gained by Fog System in Iran Power Plants

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Abstract— **Iran has a special electricity market with more than 10% annual increase in electricity demand. Gas turbine power plants are recognized as the preferable technology to meet this rapid growth since they are constructed faster than other conventional plants. However, gas turbines lose a part of their power and efficiency when the ambient temperature rises. According to V94.2 model, presented in this paper, rising ambient temperature from 15ºC to 40ºC at φ=60%, decreases output power by 15%. It means that approximately 0.6% output power is lost per each 1ºC. This degradation alone has caused electricity grid of the country to lose 2000 MW from its total capacity in summer, when electricity demand is at its peak value. To economically tackle this degradation, evaporative inlet air cooling systems are planned to be used in gas turbine power plants of Iran.**

The objective of this study is to find those V94.2 gas power plants in the country with the proper ambient conditions for fog system application and to estimate the additional power gained by Fog for each of them. In the first part of study, thermodynamic model of V94.2 is developed to show the impact of ambient conditions i.e. temperature and humidity, on performance of this turbine. In the second part, ambient condition of existing V94.2 gas turbine power plants are checked to find their potential for Fog operation. Model of V94.2 is then utilized for estimation of the additional power gained by Fog system at the defined design points. The results of this study have shown that most of the gas turbine power plants, except those located in north and west of the country, have excellent potential for Fog operation with Evaporative Cooling Potential (ECP) of 11.5-24ºC. The results also show that Fog systems in these plants can be used as power boosters to yield additional 12.5 to 26.5 MW at the defined design points; this is a matter that makes this technology also economically attractive.

Keywords— **Fog, ambient condition, gas turbine, V94.2, thermodynamic model, power augmentation**

I. INTRODUCTION

The site ambient conditions (pressure, temperature and humidity) have great impact on gas turbines (GT) net power and efficiency [1]. Among the mentioned ambient factors, pressure is rather constant for a specific power plant, however two other factors frequently change during the day and from one season to another. Any increase in ambient temperature and humidity decreases the ambient air density. Since compressor is a fixed volume machine, therefore the total mass flow rate through turbine decreases. Moreover, compressor work in warm days increases due to the deviation in pressure ratio and constant pressure line in T-S diagram (Fig. 1). All of these effects will diminish output power and efficiency of the gas turbine and are followed by loss of profit for power plants owners. The comprehensive effect of the ambient condition on performance of typical industrial gas turbines is available in [2] in which the effect of these parameters has been elaborated.

The effect of warm weather on gas turbines performance is a considerable concern in warm area of the world such as large parts of Asia and Middle East. In many parts of Iran, ambient temperature exceeds 38ºC in summer while humidity is as low as 30% [3]. There are many papers available that have evaluated the different ways for reducing the undesirable effect of high temperature on the power plant and made parametric analyse. They have shown that when the power plant is located in such a dry and warm area, the evaporative inlet cooling can be remarkably effective [4]. The most common evaporative inlet cooling systems are Fog and Media. Kakaras [5] has shown Fog can lead to better results than Media because of higher evaporative efficiency. This system is now widely known as a reliable technology and it is estimated that approximately 700 gas turbines have already been fitted with fogging systems at this time including many modern gas turbines in the world since early 1990s [6]. Bhargava et al. parametrically analysed the fogging system for different type of gas turbines and showed that fogging is effective method for the gas turbines [7].

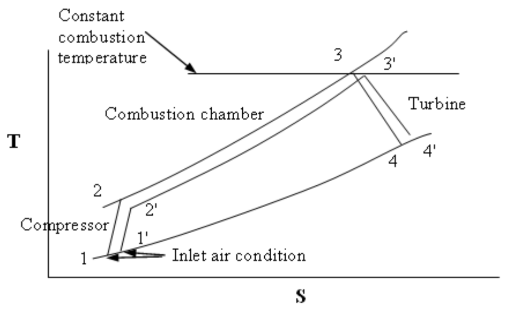


Fig. 1 Gas turbine processes diversion for a hot day on T-S diagram (1-2-3-4: normal inlet temperature status, 1'-2'-3'-4': diverted status)

However, the history of fogging in Iran shows that just a few power plants have already equipped with fogging so far. For the first time, this technology was applied for augmentation of six small Frame-5 (25 MW) gas turbines power plant in Iran in 2004 [8]. The performance test in this power plant showed that at design point, gas turbine power was increased as much as 13%.

Moreover, three large power plants, i.e. Shahid Rajaie (4 units), Ghom (2 units) and Yazd (2 units) GE Frame 9, were equipped by inlet air cooling systems in the country, with both Fog and Media. The results of this project proved that Fog advantages outweigh Media and can yield more additional power [9].

Although these projects were all proved that the country ambient condition is suitable for installation of fog system, however no project was performed for V94.2 as the common gas turbine model in Iran that has the portion of about 30% of total power generation in the country. Moreover, there are not available any research work about using fog for this type of gas turbine in the literature. The main producer of this gas turbine model has not formally released any relevant report as well. On the other hand, there was no careful calculation about additional power and the effect on fuel consumption before execution of these projects in the country and all the aforesaid papers have used the results of the system testing after installation of fog systems in order to evaluate them. However, this fact will put the projects at a financial risk because the pay-back period can not be predicted from the beginning. Another problem was that, all the described projects were performed without any consultation with the producers of the gas turbines. Therefore, operation of Fog in these power plants has caused some side effects on the units such as increasing the vibration of the turbine, water condensation in the inlet air duct, excessive condensation, rust, and compressor blades erosion. Therefore, it can be concluded that one of the main reasons for those problems, is not having enough knowledge about the material and technology of GTs among Fog suppliers.

Up to date, close cooperation of GT manufacturers and Fog suppliers is just recorded in the projects by Alstom [10]. This interaction has resulted valuable experiences and entitled this company as the only turbine manufacturer which offers optional Fog and high-Fog systems on its products [11]. Getting idea from Alstom and considering Iran excellent potential for inlet cooling [12], MAPNA, Iran manufacturer of V94.2 under license of Siemens, intended to improve the output of its operating gas turbines using Fog systems. To show that this is a beneficial approach, the following study has been conducted to estimate V94.2 output power and efficiency at the ambient condition of different existing power plants in which V94.2 GTs are operating. In this paper, the thermodynamic modeling of V94.2 gas turbine is presented based on V94.2 GT design documents and the experience gained by installation of Fog system in Iran power plants. Also, the technology has been considered to check whether water droplets can cause a risk in combustion chamber and compressor. Finally, the thermodynamic model has been utilized to calculate the additional power and efficiency in case of fogging usage as well as the effect of fog on fuel consumption based on the actual ambient condition of the power plants.

II. V94.2 GAS TURBINE DESCRIPTION

V94.2 GT, originally designed by Siemens, is a well-known medium range gas turbine which comprises of a single shaft and a single casing. It has two Silo-type combustion chambers that are assembled in two sides of turbine. This turbine has the ability of working with natural gas and gas oil. The net power and efficiency of this turbine, at ISO condition, are 157.7 MW and 34.7% respectively. This turbine has the required features for integrating evaporative inlet air cooling systems: It has dual-fine air filtration system that reduces the risk of deposit formation on compressor blades. Also, the first 6 stages of compressor blades are coated to protect them from erosion by the droplets that probably exist in air flow. Furthermore, hot blades of turbine have air-cooling passages which decrease risk of deposit and hot-spot formation due to rising steam content in combustion gases. Air inlet duct is equipped by the anti-icing system which protects bell-month from ice formation in the cold ambient. Also there has been acceptable performance of this type of turbine in the humid area of Iran (φ>90%). These features will guarantee that this turbine has the required capability for being equipped with Fog system according to [13].

III. THERMODYNAMIC MODELING OF V94.2 GT

Three main thermodynamic processes; compression, combustion and expansion corresponding to the processes 1-2, 2-3 and 3-4 of Fig. 1 for V94.2 are described and formulated below with the aim of calculating output power and efficiency of turbine as functions of the inlet air temperature and humidity (point 1 in Fig. 1). In this section, the output factors of V94.2 are calculated at ISO condition and then the model is tuned for other ambient conditions. Air is assumed to have a composition of 21% O_2 and 79% N_2.

- *Compression process 1-2*: In each gas turbine ambient air is sucked into compressor through an air channel where the temperature of the air slightly varies due to the change of Mach number. In this section this variation is not considered and the air is assumed to enter the first stage of the compressor with the same condition of the ambient air. In order to calculate the required work for compressing the air from the ambient condition to the proper pressure for combustion chamber, it is necessary to calculate the thermodynamic condition of both inlet air and outlet air of the compressor according to the V94.2 specifications.

For the modeling, the specific heat at constant pressure of the inlet air is needed. To calculate this parameter the following equations are use [1] (1)

Humidity ratio:

$$H = 0.622\frac{P_v}{P_d} = 0.622\frac{P_{ss.\Phi}}{P_a - P_v} \qquad (1)$$

Steam mass fraction:

$$SMF = \frac{H}{1+H} \qquad (2)$$

Air mass fraction:

$$AMF = 1 - SMF \qquad (3)$$

Molecular weight of mass:

$$MWM = \frac{1}{\frac{SMF}{18.015} + \frac{AMF}{28.97}} \qquad (4)$$

Gas constant for the mixture of the air:

$$R_{mixture} = \frac{8.3143}{MWM} \qquad (5)$$

Specific heat of the inlet air:

$$Cv_{a1} = Cp_{a1} - R_1 \qquad (6)$$

Density of the inlet air:

$$\rho_{a1} = (\frac{353.15}{T_{a1}})\left[1 - 0.377 \times \frac{P_{v1}}{P_{a1}}\right] \qquad (7)$$

Specific heat of the moisture and the dry air [2]:

$$Cp_s = \left[\begin{matrix} 32.24 + 0.001923T + 1.055*10^{-5}T^2 \\ -4.187*10^{-9}T^3 \end{matrix}\right]/18.015 \qquad (8)$$

$$Cp_d = \left[\begin{matrix} 28.11 + 0.001967T + 0.4802*10^{-5}T^2 - \\ 1.966*10^{-9}T^3 \end{matrix}\right]/28.97 \qquad (9)$$

and finally the specific heat of the air:

$$Cp_{a1} = Cp_{d1} + H * Cp_{s1} \qquad (10)$$

After calculation the inlet air condition, the air condition coming out of the compressor should be determined. For this purpose, the compressor outlet isentropic temperature is calculated first and then actual outlet conditions will be determined using compressor efficiency.

Compressor outlet isentropic temperature:

$$T_{2s} = T_1(PR)^{\frac{K-1}{K}} \quad , K = \frac{K_1 + K_2}{2} \qquad (11)$$

According to V94.2 specifications [14], Thermal efficiency of compressor is 87% and at ISO condition pressure ratio of the compressor is 11.3. Nevertheless, Pressure ratio (PR) changes at different ambient conditions, whereas compressor isentropic efficiency is almost constant.

the first thermodynamic law is applied as follows:

$$(T.C_P)_{act2} = \frac{(T.C_P)_1 - (T.C_P)_{S2}}{\eta_{comp}} + (T.C_P)_1 \quad (12)$$

Air actual outlet temperature (T_{act2}) with its corresponding specific heat (C_p) can be determined by Eq. (12).

After defining the actual output conditions, required work of the compressor can be found:

$$W_{1-2} = (C_pT)_2 - (C_pT)_1 \quad (13)$$

- *Combustion Process 2-3*: In V94.2, compressed air is used for three purposes. The main part which is approximately 92% of the total flow is led to the combustion chamber for combustion. The second part, about 3% of the total flow, mainly extracted from the last stage of compressor, passes through cooling passages of turbine hot blades (first two rows) for cooling of the hot parts. The last remaining part of the compressed air is consumed by the auxiliaries of the gas turbine, such as anti-icing system and air filter pulse jet systems. This means that totally 92 per cent of the outlet air of compressor participates in the combustion process.

Design fuel of V94.2 is methane. To improve the combustion efficiency, before the fuel is injected in the combustion chamber through the burners, it is pre-heated to 30 ºC by getting the heat of the compressed air on its way to combustion chambers. At ISO condition, the mass flow of fuel is 9.1 Kg/s and the total mass flow of compressor is 493.86 Kg/s [14]. This combination of air and fuel mass provides the fuel to air mass flow ratio (F/A) of 0.02 to the combustion chambers. However, F/A changes at other ambient conditions therefore it shall be calculated for other ambient conditions.

Processes in combustion chamber are divided into two following parts. The aim is calculation of the heat due to combustion. Therefore, the specific heats of the inlet air/fuel and the flue gases generated due to the combustion are required.

a) Before combustion (point 2 in Fig. 1): When air and fuel enters the combustion chamber the condition of the air entering combustion chamber is assumed to be the same as the compressor outlet one, determined by Eq.12.

Condition of the inlet fuel is defined as it follows:

Specific heat of the fuel [2]:

$$C_{pf} = -672.87 + 439.74\theta^{0.25} - 24.875\theta^{0.75} + 323.88\theta^{-0.5}, \theta = \frac{T}{100} \quad (14)$$

Specific heat of the fuel and air mixture:

$$C_{p\,m2} = C_{p\,a2} + (f/a)C_{p\,f} \quad (15)$$

b) After combustion (point 3 in Fig. 3): The products of the combustion are called flue gases.

$$CH_4+5.82(O_2+3.76N_2) \rightarrow CO_2 + 2H_2O + 3.82O_2 + 21.88N_2 \quad (16)$$

The specific heat (C_p) of the hot flue gases, CO_2, O_2, N_2, in large gas turbines, such as V94.2, for two different F/A are presented by [2] as follows. For other F/A, C_p shall be calculated by interpolation.

$$Cp_p = 1.01 + 0.32(\frac{T_3 - 400}{1400} - 0.04(\frac{(T_3-400)^2}{1400}) \quad \text{For F/A=0.0135} \quad (17)$$

$$Cp_p = 1.03 + 0.32(\frac{T_3 - 400}{1400} - 0.02(\frac{(T_3-400)^2}{1400}) \quad \text{For F/A=0.027} \quad (18)$$

Flue gases also contain some amount of H_2O. This moisture is due to both the product of combustion and the humidity of the ambient air that are carried into the combustion chambers. The specific heat of the moisture must also be taken into consideration to complete the model of this part of GT:

$$Cp_{m3} = Cp_{p3} + H * Cp_{s3} \quad (19)$$

After calculation of specific heat of inlet air/flow and flue gases including the moisture, it is now possible to calculate the total released heat per unit mass passing through combustion chamber. Temperature of flue gases leaving the combustion chamber of V94.2 is 1060 °C [14]. The released heat as a result of combustion is presented below:

$$Q_{2-3} = \int_{T2}^{T3} [Cp_{m3}(T) * T_3 - Cp_{m2}(T) * T2] dT \quad (20)$$

- *Turbine Process 3-4*: Hot gases with the mentioned mass and specific heat of Cp_{m3} enter the turbine, rotate the shaft and will expand as a result. To calculate the power gained by this expansion, the specific heat of the exhaust flow shall be calculated. For this purpose, first the isentropic temperature of exhaust flue gases (T_{4s}) has to be determined:

$$T_{4s} = \left(\frac{P_4}{P_3}\right)^{\frac{K-1}{K}} * T_3, \text{Where } P_4/P_3 = PR \qquad (21)$$

In order to calculate the C_p of the exhaust gases that leave the turbine, composition of gases is needed. As mentioned before, at ISO conditions, F/A=0.02. Therefore, based on this ratio and Eq. 16, the composition of exhaust gases will be according to the following Table.

TABLE 1
Composition of V94.2 GT exhaust gases

Product Components	mass fraction
CO_2	0.0539
H_20	0.0441
O_2	0.1500
N_2	0.7519

The specific heat of the composition is calculated from the individual specific heats and mass fractions:

$$C_{P\,mix} = m_{fa} C_{P\,a} + m_{fb} C_{P\,b} + ... \qquad (22)$$

According to [14] temperature of exhaust gases at ISO conditions is 539°C. The hot flue gases should reach to this temperature through a 91%-efficiency turbine. The following equations are used for determining exhaust specific heat (C_{pm4}). It is assumed that the efficiency remains constant.

The first thermodynamic law is applied as follows:

$$(TC_{PP})_{4act} = \frac{(TC_{PP})_{4s} - (TC_{Pp})_3}{\eta} + (TC_{Pp})_3 \qquad (23)$$

Having specific heat of the products (Eq. 23) and moisture, the specific heat of the mixture, the exhaust flow can be calculated as it follows:

$$C_{P\,m4} = C_{P\,p4} + H.C_{P\,s} \qquad (24)$$

Generated work by turbine is:

$$W_{3-4} = (C_{Pm} T)_4 - (C_{Pm} T)_3 \qquad (25)$$

and efficiency of the turbine can be estimated:

$$\eta_{th} = (W_{3-4} - W_{1-2}) / Q_{2-3} \qquad (26)$$

The heat rate is calculated as follows:

$$HeatRate = \frac{3600}{\eta} \left(\frac{KJ}{KWh}\right) \qquad (27)$$

The net power is estimated as it follows:

$$W_{net} = (W_{3-4} \times \dot{m}_{gas} - W_{1-2} \times \dot{m}_a) \qquad (28)$$

where:

$$\dot{m}_a = 405.8 \times \rho_a \qquad \dot{m}_{gas} = 0.92 \times \dot{m}_a + \dot{m}_f$$

IV. HANDLING THE MODEL AT DIFFERENT AMBIENT CONDITION

The above equations together will form the thermodynamic model of V94.2 gas turbine. This model converts input data, i.e. temperature, pressure and humidity of the ambient air, to output data of the gas turbine, i.e. net power, efficiency and fuel consumption. Using this model, V94.2 GT thermodynamic data and output factors at ISO condition are calculated and shown in table (2). As it is clear, the calculated output and efficiency of the turbine is consistent with the catalogue design data of the turbine, [14], with an acceptable accuracy. In order to calculate the net power, efficiency and fuel consumption at other ambient conditions than ISO, the following steps have to be followed:

1- Any change in ambient condition leads to change in compressor inlet air condition (ρ, c_p, k, H). Therefore, these parameters have to be calculated again for any new condition.

2- Compressor pressure ratio is affected by ambient condition. For ambient temperatures other than 15°C, pressure ratio (PR) has to be corrected from V94.2 compressor map and compression process has to be calculated accordingly by the model.

3- Changing the combustion chamber inlet condition (T, C_p, φ) as a result of change of ambient conditions will affect fuel mass flow, F/A and gas compositions. Therefore these parameters have to be re-calculated for each new condition.

4- Change in combustion chamber pressure and fuel consumption will affect the condition of turbine inlet gas (except for temperature which is always kept fixed by GT control system) as well as turbine pressure ratio and exhaust temperature. Therefore these parameters also have to be re-calculated for each condition.

TABLE 2
Comparison of calculated model results with design values at ISO condition

Item	Unit	Calculated value	Design value [11]
Air inlet mass flow	Kg/s	493.86	---
PR	---	11.3	11.3
Comp outlet temp	°C	341	---
Fuel mass flow	Kg/s	9.1	9.1
Flue gas temp	°C	1060	1060
Turbine outlet temp	°C	539	537.3
Total mass flow	Kg/s	503	508
Turbine net power	MW	157.2	157.7
Efficiency	%	34.6	34.7
Heat rate	KJ/KWh	10404.6	10374.6

To calculate the changes of the thermodynamic factors of V94.2, a numerical model was developed. Based on the range of temperature, pressure and humidity which normally exist at different areas of Iran during the year, the output factors of the turbine, as well as fuel consumption were calculated by the model and is presented in the next section. Since the purpose of this model is to estimate the impact of high temperature on the turbine operation as well as calculation of the additional power that would be gained for fog system application, it is important to have the output of the model in form of characteristic graphs at wide various ambient conditions.

V. EFFECT OF AMBIENT CONDITION ON V94.2 GT

Applying V94.2 thermodynamic model at different ambient conditions, clearly shows why the higher ambient temperatures lead to reduce the turbine output. The higher temperature equals to the lower air density and since the rotational speed of the turbine is fixed, it causes less mass flow of air to pass through the compressor. The result will be less fuel consumption in the combustion chamber since the air/fuel ratio is kept constant during normal operation of the turbine. Decreasing the air and fuel mass flow in combustion chamber, results in less mass flow of hot gases through the blades and finally decline in output power of the turbine. The impact of increasing ambient condition on inlet mass flow of the air for V94.2 as well as the effect of temperature on fuel consumption are estimated by the model and shown in Figs. 2-3. In order to estimate the output of V 94.2 at different ambient conditions, the model was used to calculate net power and efficiency at different ambient temperature and humidity. Figs 4-5 show the output of the model. To calculate net power and efficiency the following equations are needed. (29)

$$P_{(T,\varphi)}(MW) = K_{P,\varphi} \times P^* \times 157.7 \quad (29)$$

$$\eta_{(T,\varphi)}(\%) = K_{\eta,\varphi} \times E^* \times 34.7 \quad (30)$$

For estimation of $K_{P,\varphi}$, P*, $K_{\eta,\varphi}$ and E^*, please refer to Figs.4-7.

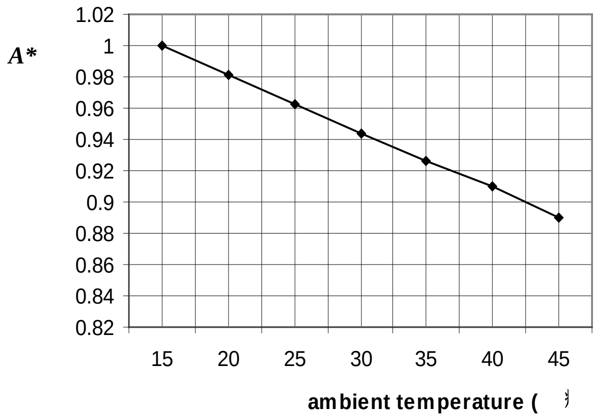


Fig 2. Effect of ambient temperature on inlet air mass flow (A*) at relative humidity of 60% (A* is ratio of gas turbine inlet air mass flow at the given condition to inlet air mass flow at ISO)

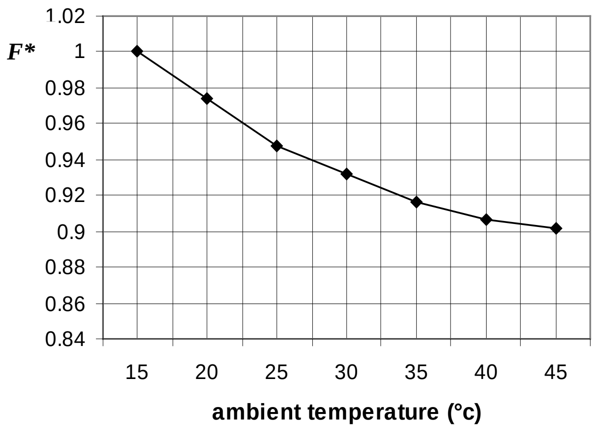


Fig 3. Effect of ambient temperature on fuel consumption (F*) at relative humidity of 60% (F* is ratio of gas turbine fuel consumption at the given condition to fuel consumption at ISO)

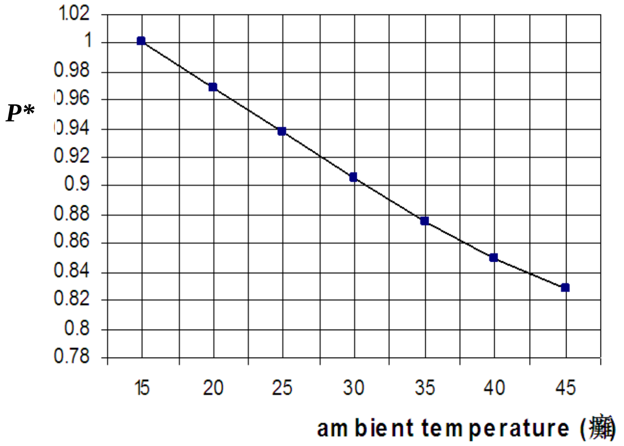


Fig 4. Effect of ambient temperature on net power (P*) at relative humidity of 60% (P* is ratio of turbine net power at the given condition to turbine net power at ISO)

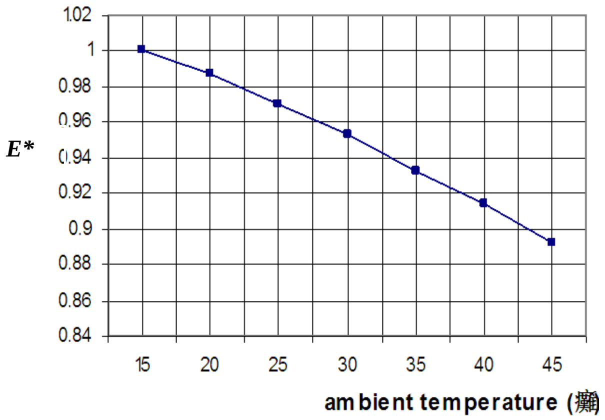
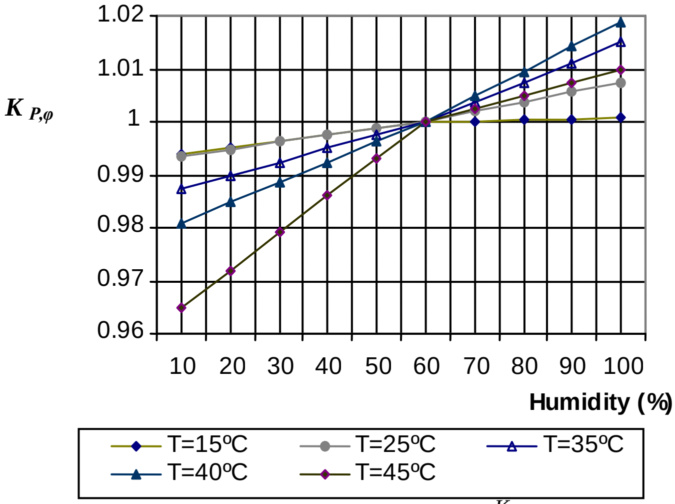


Fig 5. Effect of ambient temperature on efficiency (E*) at relative humidity of 60% (E* is ratio of turbine efficiency at the given condition to turbine efficiency at ISO)

The above graphs show how much the performance of V94.2 is dependent on the ambient temperature. For example, increasing the temperature from 15 to 40°C will reduce the output of the turbine and efficiency as much as 15% and 8.5% , respectively. Humidity is another ambient factor that affects V94.2 performance. Humidity can either increase or decrease net output power of V94.2 depending on the air specific humidity and temperature. As is shown in Fig. 6, for the relative humidity ratios below 60%, the effect of this factor is enhanced by increase of ambient temperature. For instance at 40°C and 20% humidity the V94.2 output power will decrease by as much as 2.8% (compared to ISO).



$K_{P,\varphi}$

On the other hand, the relative humidity higher than 60% along with lower temperatures has opposite effect on the turbine as it will increase power and reduces efficiency. For instance, if the ambient condition changes from 40°C and 20% humidity to 25°C and 90% humidity, the adverse effect of humidity on net power is omitted. Moreover, V94.2 will deliver more power than its nominal value. This improvement will happen along with more fuel consumption. However, since the electricity network has high demand in summer time, it is quite desirable to consume more fuel for gaining more power

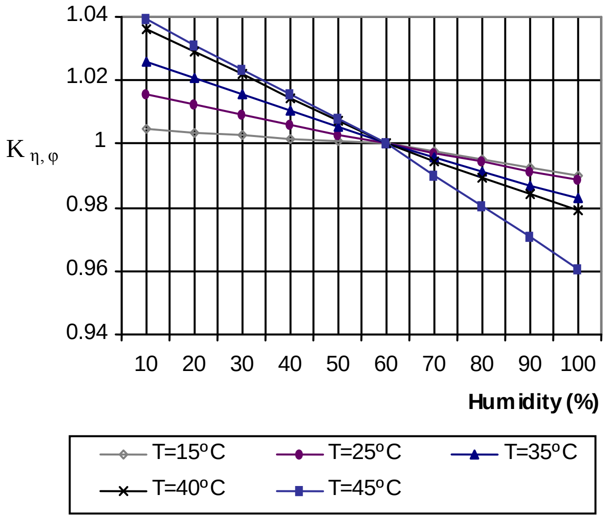


Fig 7. Correction factor for turbine efficiency ($K_{\eta,\varphi}$) versus relative humidity for different ambient temperatures from 15ºC to 45ºC

The above graphs show that any decrease in temperature and increase in humidity to more than 60%; will increase the generated power by the turbine. This new condition is exactly what is achievable by the fog system.

VI. POTENTIAL OF IRAN V94.2 POWER PLANTS FOR FOG OPERATION

There are totally 13 giant power plants in Iran with 12000 MW installed capacity that use V94.2 gas turbines. Considering the total installed capacity i.e. 45000 MW, the portion of V94.2 GTs in power generation in the country is currently 26% and it is increasing rapidly due to the fact that each year twenty five V94.2 gas turbine units are installed and added to the network. Many of the power plants using V94.2 are located in warm and dry areas of the country with the average temperature of more than 38°C in summer. Considering the output graphs of V94.2 model and above proofs, it is clear why every year the country faces serious loss of electricity generation during the summer time and cannot deliver the planned electricity. Table (3) presents the name and location of the power plants V94.2 gas turbines. The installed capacity and the nominal capacity are also shown in the table.

TABLE 3
FOP and design point of Iran V94.2 gasturbine power plants

Power plant name	no. of units	location	elevation (m)	Installed capacity (MW)	nominal capacity (MW)	FOP hr/year	FOP (ºC.hr)/year	Design point T	Design point RH
Abadan	4	south	6.6	631	630.4	2022	35082.6	46	10
Asalooyeh	12	south, costal	7	1892	1891.2	1478	18744.6	40	42
Chabahar	2	south, costal	8	315	314.2	1354	17564.2	37.5	74
Esfahan	6	center	1550	946	784.8	1011	17996.4	40	11
Jahrom	6	east	1100	946	832.1	1098	16933.8	38	20
Kazeroon	6	south west	735	946	860.4	1200	19751.7	39	10
Kerman	8	center south	1753	1262	1033.8	1101	19300.2	39	10
Khoramabad	8	south	1147	1262	1105.7	1278	22600.5	41.8	9
Mashhad	6	north east	992	946	848.2	645	9756	37	9
Oroomieh	4	north west	1328	631	543.4	279	3255	33.5	23
Parand	6	center north	1312	946	816	648	9627.3	38	15
Shirvan	6	north east	1392	946	803.7	738	9445.5	34	15
Yazd	2	center south	1237	315	271	2211	23971.5	40.8	9

In order to have an idea about the ambient temperature of these power plants and to check the feasibility of application of fog system for them, the design point and fog operation potential (FOP) of the power plants were calculated by using local meteorological data based on the following explanations. FOP and design point of the named power plants are shown in table (3).

- The design point is the highest temperature and its respective humidity (T_{db} ,φ) that occurs more than 50 hours per year. This factor corresponds to the highest optimized evaporative cooling potential (ECP) and ($T_{db} - T_{wb}$). The potential for evaporative air cooling at the design point has its maximum value [13].
- The FOP is actually the number of hours per year when temperature is more than 30°C and the relative humidity is less than 60%. This is the minimum condition that must occur so that fog system can run effectively and economically. The power plants with the higher FOP have the higher potential for using fog system [13].

According to this definition, as seen in the table, nine power plants have excellent potential for evaporative inlet air cooling because their design temperature and FOP are more than 38°C and 1000 hours, respectively. It means fog can effectively operate in these power plants for more than 1000 hours per year. Other four power plants are still suitable for evaporative cooling despite having lower FOP. This is due to the fact that their design temperature is still high compared to the power plants that are equipped with fog system in Europe.

In spite of such excellent potential in the country for evaporative air cooling applications and the serious problem in meeting electricity demand in summer, none of these power plants have yet been equipped with fog system. In fact, the authorities attempt to meet the demand by making new power plants that is of course a more expensive and time-consuming solution compared to fog system alternative.

VII. RESULTS

In order to assess the potential of the power plants for fog application, the V94.2 model was run to calculate the output of each V94.2 in those power plants. According to table (4), the total generated power of those power plants in hot days of summer is 9054 MW. A comparison between the generated output power in hot days and the nominal output power of those power plants are shown in table (4).

TABLE 4
Fog Design point and additional power gained by fog system for V94.2 gas turbine power plants

Power plant name	Output of one V94.2 unit Before fog at design point				Output of one V94.2 unit After fog				Additional MW	Total net power without fog (MW)	Total net power with fog (MW)
	T	RH	MW	Efficiency	T	RH	MW	Efficiency			
Abadan	46	10	124.71	32.03%	22	95	151.26	34.08%	26.55	498.84	605.04
Asalooyeh	40	42	133.02	31.98%	28.5	95	145.53	32.85%	12.51	1596.24	1746.36
Chabahar	31.5	74	141.65	32.53%	28	95	145.57	32.85%	3.92	283.3	291.14
Esfahan	40	11	109.19	32.77%	19	95	127.53	33.91%	18.34	655.14	765.18
Jahrom	38	20	117.72	32.63%	22	95	133.11	34.08%	15.39	706.32	798.66
Kazeroon	39	10	120.36	32.78%	18	95	140.97	34.05%	20.61	722.16	845.82
Kerman	39	10	108.45	32.78%	18	95	127.03	34.05%	18.57	867.6	1016.24
Khoramabad	41.8	9	114.05	32.61%	19.5	95	134.47	33.88%	20.42	912.4	1075.76
Mashhad	37	9	120.15	32.93%	17	95	139.25	34.05%	19.09	720.9	835.5
Oroomieh	33.5	23	119.03	33.08%	19	95	132.31	33.91%	13.29	476.12	529.24
Parand	38	15	115.56	32.63%	20	95	132.32	33.84%	16.76	693.36	793.92
Shirvan	34	15	116.35	32.39%	17.5	95	131.81	34.01%	15.46	698.1	790.86
Yazd	40.8	9	112.24	32.75%	19	95	132.14	33.91%	19.90	224.28	264.28
									Total (MW)	9054.76	10358

It reveals that in hot days of the year the country losses 1680 MW of the capacity of the power plants. This happens exactly at the time when the demand of the electricity is in its peak value. That is while, evaporative inlet air cooling systems such as fog is can be considered as an effective solution to compensate for power loss in an effective way.

To see the effect of fog on the power plants, the temperature reduction and amount of enhanced output power in hot days were calculated by the V94.2 model and presented in table (4). For estimation of the additional power gained by fog systems, the effectiveness of fog was considered to be 95%. It means that the relative humidity of the air leaving fog nozzles is 95%. Furthermore, fog system is considered to be used during the periods of the year in which T>30ºC and φ<50%., according to the FOP of each power plants.

Finally, the following comparison between the output of the power plants at design point in two states; with and without fog, clearly shows that the augmentation of V94.2 GT with fog system is excellent for the most power plants. According to the results of this study, equipping those power plants with fog system can help the network to increase its capacity in hot days of summer from 84% (without fog) to 96% (with fog) of the nominal capacity and solve the problem of power loss in summer.

VIII. CONCLUSIONS

The model of V94.2 GT was developed in this paper and verified by the catalogue information and actual output of the operating V94.2s. The output of this model shows remarkable impact of ambient condition, especially high temperature, on the performance of V94.2. Moreover, it has shown the reason why Iran faces power loss in the peak period of the year which happens in summer. Analysing the ambient condition of the power plants with operating V94.2 in Iran, revealed that majority of these plants are located in dry regions with average day temperature more than 38°C in summer. In such conditions, according to the results of the model, V94.2 performance is utterly deteriorated so that it can hardly generate more than 84% of its nominal power. On the other hand, looking at the meteorological data of these power plants site locations has shown that they mainly have an excellent potential for evaporative inlet air cooling as a method for reducing the temperature in summer and increasing the density of the inlet air to the turbines. Consequently, the model was run to calculate the additional power that can be gained by fog system, as the most efficient evaporative air cooling method. The comparison between the output power of the turbines without and with fogging showed that fog system can help the power plants to improve their outputs as much as 12% (dependent on different power plants: from 12 to 26 additional MW) and to get closer to their nominal capacity even in the hot days of summer. The result of this study provides an effective tool for the owners of the power plants as well as state authorities to check the power loss due to rising the ambient temperature in different power plants and then to calculate the additions power that can be generated with cooling the inlet air by fog system. This will help to find out which power plants are suitable for fog system installation and will facilitate switching to this economic and fast solution of V94.2 power augmentation instead of just focusing on installing new power plants for meeting the power demand in the country in summer time. It is also worth for conducting economic and cost-benefit analysis to evaluate whether fog can bring needed benefits or not.

NOMENCLATURE

A	Air mass flow, Kg/s
A*	Ratio of gas turbine inlet air mass flow at the given condition to inlet air mass flow at ISO
AMF	air mass fraction
C_P	specific heat at constant pressure, KJ/Kg K
C_V	specific heat at constant volume, KJ/Kg K
E*	Ratio of turbine efficiency at the given condition to turbine efficiency at ISO
ECP	Evaporative cooling potential
F	Fuel mass flow, Kg/s
F*	Ratio of gas turbine fuel consumption at the given condition to fuel consumption at ISO
FOP	Fog operation potential
GT	gas turbine
H	Humidity ratio, Kg moisture/Kg dry air
H	enthalpy, KJ/Kg
$K_{P,\varphi}$	Correction factor of turbine net power for different humidity
$K_{\eta,\varphi}$	Correction factor of turbine efficiency for different humidity
M	molecular weight
MW	mega watt generated by V94.2
MWM	molecular weight of mass
P	pressure, Pa
P*	Ratio of turbine net power at the given condition to turbine net power at ISO
PR	Pressure ratio (compression and expansion)
Q	heat
R	gas constant, KJ/Kg K
RH	Relative humidity, %
SMF	steam mass fraction
T	temperature, K
T_{db}	dry bulb temperature
T_{wb}	wet bulb temperature
W	net power per unit mass of air, KJ/Kg of air
η	thermal efficiency
ρ	density, Kg/m^3
φ	Relative humidity, %
Subscripts	
a	ambient air
act	Actual state
comp	compressor
d	dry air
f	Fuel
in	Input
m	mixture
p	products
s	Moisture, isentropic
ss	Saturated vapour
t	turbine
v	vapour

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