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Steam-Injected GT Cycles Offer More Power in a Hot Season

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ABSTRACT

It is said that gas turbine generating plants on simple cycle reduce the power output by 3% in variation with 1% increase of ambient temperature change. When maintaining maximum cycle temperature, i.e., turbine inlet temperature (T4), the reduction of temperature ratio cannot be avoided by increasing minimum cycle temperature, i.e., ambient temperature (T2). Accordingly, the useful power output must be reduced and the thermal energy would be emitted into the atmosphere. The widely used combined cycle plant is an idea to recover the not-used thermal energy into the power, and it is still losing power by 2% in variation with 1% of the ambient temperature. In order to recover effectively such waste thermal energy into the power output, many ideas are adopted to mainly aim the thermal efficiency exceeding 60%, like "Steam-Cooled Combined Cycle", "Kalina Cycle" etc.[*1, *2, *3, *4, *5]

It was confirmed that the water/steam-injected WI/GAS3D GT version of modified LM6000 could produce 106 MW with 56% thermal efficiency at ISO conditions[*6], and it is demonstrated, this time, that the power curve of the plant in variation with ambient temperature is very flat, comparing with those of conventional GT plants. It might be recommended to establish advantageous cycle plants using the more advanced gas turbines derived from like GE90, PW4000, and Trent800, in order to get exceeding 60% thermal efficiency in hot climate conditions, and it would be expected that such technology application might contribute to execute the worldwide COP3 agreement by saving the fossil fuel usage, resulting in minimal CO2 emissions.

NOMENCLATURE

A**	Turbine Effective Nozzle Area
COB	Abbreviation of Combustor
Cp	Specific Heat at Constant Pressure
G**	Mass Flow at each station
Hw**	Latent Heat of Water
HPC	Abbreviation of High Pressure Comp.
HPT	Abbreviation of High Pressure Turbine
HRSG	Abbreviation of Heat Recovery Steam Generator
I**	Index for Water/Steam Injection defined as (1+Gw/Ga)
J**	Latent Heat Enthalpy Index defined as H/Cpa/Ta
K**	Temp. Difference Ratio Index defined as (To-Ti)/Ti
L**	Mixing Temp. Difference Ratio defined as (Tw-Ta)/Ta
LPC	Abbreviation of Low Pressure Comp.
LPT	Abbreviation of Low Pressure Turbine
m**	Temp. Rise/Drop Index
MPC	Abbreviation of Medium Pressure Comp.
MPT	Abbreviation of Medium Pressure Turbine
P**	Pressure at each station
PW	Shaft Horsepower at GT Coupling
PWT	Abbreviation of Power Turbine
QP	Specific Heat Rate
R	Gas Constant: air; 287.0, steam; 461.7 J/kg/K
S**	Specific Heat Difference Ratio Index as (Cps-Cpa)/Cpa
T**	Temperature at each station
X**	Shaft Speed
Wf	Fuel flow

Suffix

a	Air (Molecular Weight: 28.96)
g	Combustion Gas or Mixed Gas
s	Steam (Molecular Weight: 18.01)
w	Water

Numbering suffix

2	Compressor Inlet (LPC Inlet)
24	LPC Outlet
25	MPC Inlet
27	MPC Outlet
28	HPC Inlet
3	Compressor Outlet (HPC Outlet)
34	Combustor (COB) Inlet
4	Combustor (COB) Outlet
41	Turbine Inlet (HPT Inlet)
42	HPT Outlet
44	MPT Inlet
46	MPT Outlet
47	LPT Inlet
48	LPT Outlet
49	Power Turbine Inlet (PWT Inlet)
8	Turbine Outlet (PWT Outlet)
91 thru 98	Corresponding to HRSG Components
100(am)	HRSG Outlet (Economizer Outlet)

1. INTRODUCTION

The typical power characteristics of LM6000 simple cycle plant are shown as below in variation with ambient temperature. It can be seen that LM6000 will lose 3.3% power output by 1% ambient temperature increase in normal days, and it must lose 5.4% output in very hot days, requiring T3 control, as shown in Fig. 1. These characteristics are very common even in conventional type gas turbines, because P3 control is selected to ensure the life of thrust bearings, and T4 control is adopted to secure the strength of hot path parts, and T3 control must be set to maintain the cooling effectiveness. Such control philosophy method shall be unchanged in any gas turbine plants.

The power characteristics are summarized as in Table 2 for different control parameters. The power differential figures (dPW/PW) with ambient temperature differential figures (dT2/T2) in various control modes, are listed in the bold-type underlined expression.

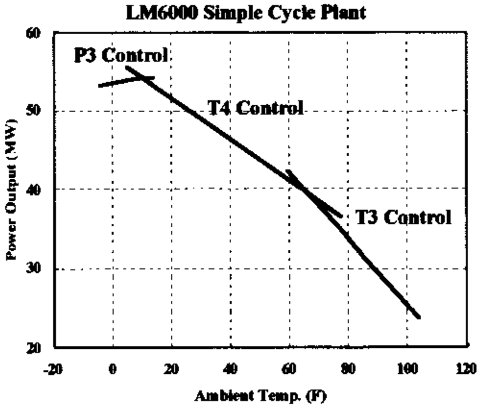

Fig.1 Power Output vs. Ambient Temp.

	dP2/P2	**dT2/T2**	dI24/I24	dI3/I3	**dP3/P3**	dP8/P8
dPW/PW	-0.2	**0.5**	-1.7	-0.7	1.8	0.5
dQP/QP	-0.1	0.0	0.4	-1.4	-0.4	-0.5

	dP2/P2	**dT2/T2**	dI24/I24	dI3/I3	**dT4/T4**	dP8/P8
dPW/PW	1.5	**-3.3**	16.1	6.7	3.8	0.5
dQP/QP	-0.5	0.9	-3.6	-3.1	-0.9	-0.5

	dP2/P2	**dT2/T2**	dI24/I24	dI3/I3	**dT3/T3**	dP8/P8
dPW/PW	1.5	**-5.4**	28.9	-0.7	5.9	0.5
dQP/QP	-0.5	1.3	-6.5	-1.4	-1.3	-0.5

Table 1 Power Variation with T2, under Various Control

It should be noted that heat rate figures (dQP/QP) in addition to power output (dPW/PW) are getting worse by increasing ambient air temperature (dT2/T2), and some measures must be considered for performance deterioration in hot days.

Although the popular method to increase the power is the adoption of a steam bottoming cycle, such recovery method would not be enough due to intrinsically poor "Rankine" cycle due to the moderate temperature of 1000 F (810 K) or less class.

In order to overcome the demerits, it might be appropriate to heat up the steam to 2500 F (1700 K) or higher, by mixing in a main gas stream. Mixed gas-steam cycles, however, have considerable impacts to the basic GT cycle mainly due to the specific heat increase by steam mixing, and due to the bigger mass flow in the turbine by steam injection.

The operational parameters' changes, therefore, by water/steam mixing (dI24/I24, dI3/I3, dI42/I42 etc.) should be evaluated to confirm not exceeding operational limits of GT itself, like revolutional speed and air/gas pressure values, according to the performance analysis method which is already discussed[5].

2. MODELING OF LM6000 GT PLANT

The LM6000 is of multiple shaft type with bleed ports, suitable GT for intercooling and/or steam injections. It can have better thermal efficiencies as the evaporated steam to be worked in much higher temperature region by being injected into the main gas.

The concept of steam injected GT is not new, since early 1980's, really steam injected gas turbines have been successfully operated with middle 40's thermal efficiency level.

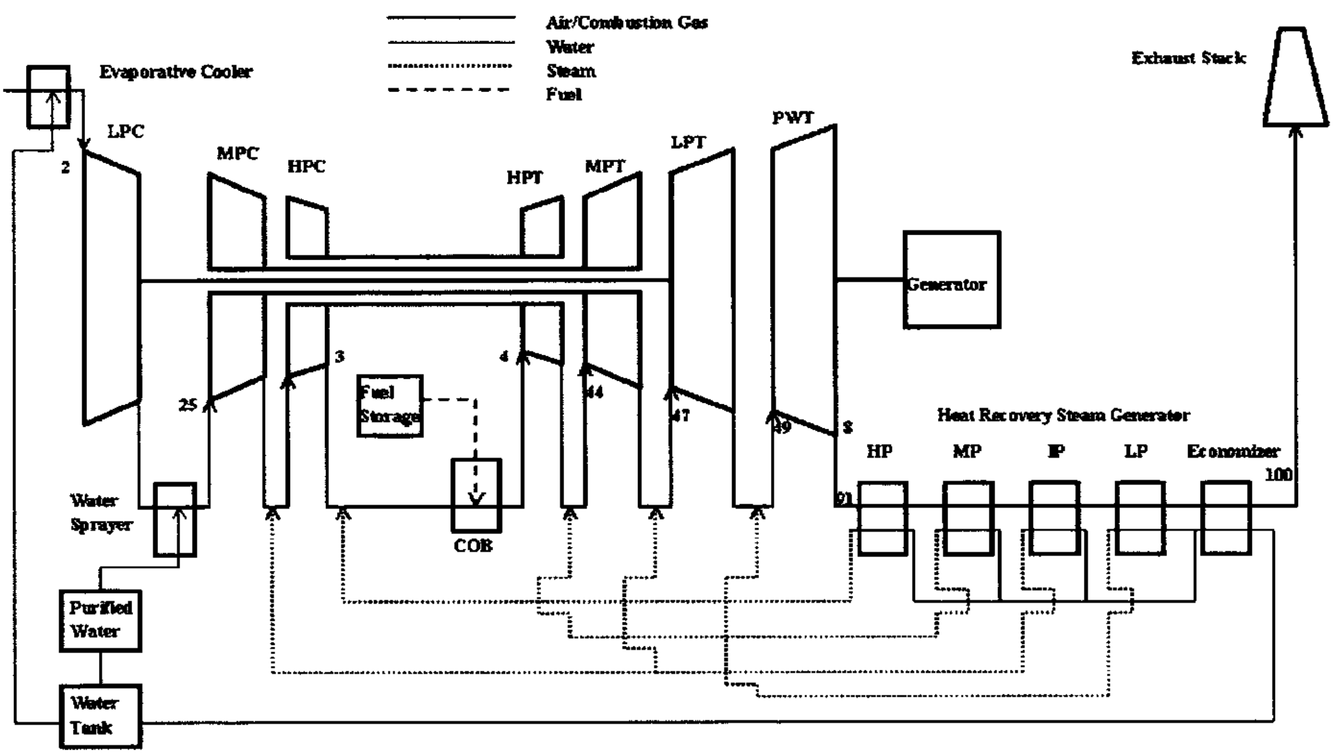

Fig. 2 Cycle Flow Diagram

The rated HPT inlet temperature is 1570 K (2367 F), which is lower than the take-off rating of aircraft, and the leading particulars are as follows.

Conditions	101.3 kPa (14.7 PSIA) Ambient Pressure
	288.2 K (59.0 F) Ambient Temperature
	4.0 kPa (16.0"H2O) Inlet Duct Losses
	2.6 kPa (10.4"H2O) Exit Duct Losses
Configuration	Standard Dry
Power Output	41.3 MW @ GT Coupling
Efficiency	42.1 % @ GT Coupling
Suction Air Flow	121 kg/s (266 lb/s)
Pressure Ratio	30.0
HPT Inlet Temp.	1,570 K (2367 F)
GT Exit Temp.	731 K (856 F)

3. STUDY RESULTS OF VARIOUS CYCLE GT

3.1 INTERCOOLED GAS TURBINE

INDIRECTLY INTERCOOLED GT (ICAD)

The air from LPC (T24) is intercooled down to 305 K (90 F) prior to MPC inlet (T25), indirectly through a heat exchanger by the supply of 298 K (77 F) city water (Tw).

The cooling effectiveness is to be defined as (HPT Inlet Temp. - Nozzle Bulk Temp.)/(Nozzle Bulk Temp. - Cooling Air Temp.), and in this case, this effectiveness is assumed to be kept constant.

Newly raised HPT temperature is calculated as:

$T4 = (1150 - 750)*(1570 - 1150)/(1150 - 808) + 1150 = 1641$ K

Taken into account the cooling air temperature rise, newly rated HPT Inlet Temp. (T4) should be settled at 1620 K (2457 F), i.e., 50 K (90 F) raised from the original figure of 1570 K (2367 F).

Any parameters including power output (PW) can be settled by the transfer matrix formulae. The resultant leading particulars are:

Configuration	4% larger HPT and 3% Smaller PWT Nozzles
Power Output	77.1 MW @ GT Coupling
Efficiency	47.4 % @ GT Coupling
Suction Air Flow	176 kg/s (389 lb/s)
Intercooled Temp.	305 K (90 F)
Pressure Ratio	41.9
HPT Inlet Temp.	1,620 K (2,457 F)
GT Exit Temp.	701 K (802 F)

It is apparent that T3 control is meaningless by the intercooling prior to MPC, and the power curve steepness of ICAD LM6000 is nearly same as that of simple Dry GT, as shown in Fig. 4.

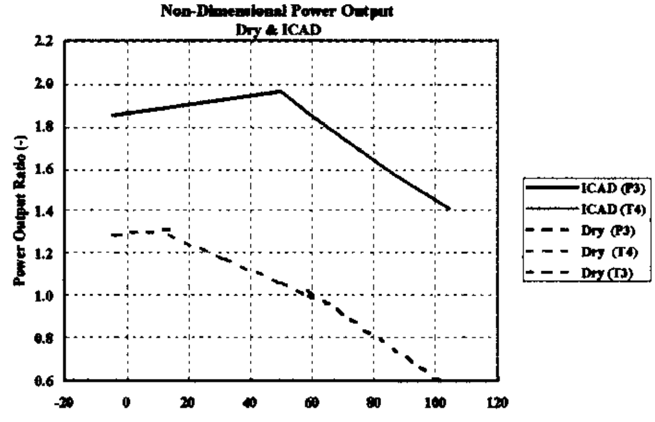

Fig. 4 Power Variation with Ambient Temp.

It would be granted for the gas turbine as a triple shaft engine type, because of investigating the impacts of steam injections in the middle of compression and expansion processes, i.e., mid-HPC and mid-HPT. The flow diagram is shown in Fig. 2, where the core HPC is divided into MPC and HPC, and the core HPT is hypothetically separated into HPT and MPT.

It is to investigate parameters of the intercooled cycle with steam injection at the existing different ports to check whether the resultant pressure ratio and shaft power are within the specified limits or not, by the performance transfer matrix.[*5,*6]

DIRECTLY INTERCOOLED GT (WI)

The particulars changes by directly intercooling are as below.

Configuration	6% smaller HPT and 3% Smaller PWT Nozzles
Power Output	75.4 MW @ GT Coupling
Efficiency	48.6 % @ GT Coupling
Suction Air Flow	162 kg/s (358 lb/s)
Water Injection	4.8 kg/s (10.6 lb/s)
Intercooled Temp.	311 K (99 F)
Pressure Ratio	41.9
HPT Inlet Temp.	1,620 K (2,457 F)
GT Exit Temp.	689 K (802 F)

The power curve in variation with ambient air temperature is shown in Fig. 5.

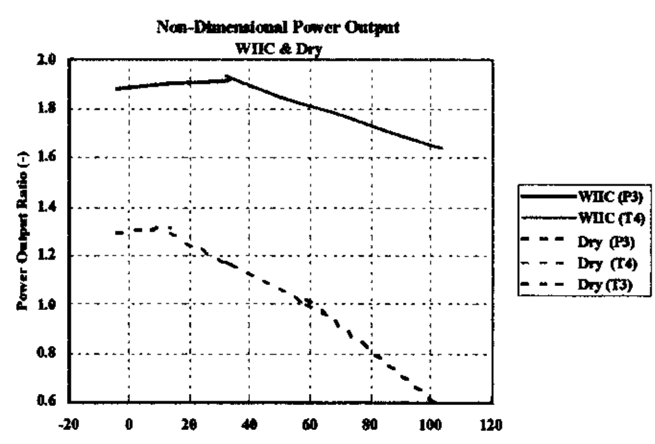

Fig. 5 Intercooled GT by Water Injection

It is seen that the performance particulars of WI LM6000 is a little bit better than those of ICAD LM6000 and WI LM6000 power curve is less sensitive than ICAD LM6000 for the variation of ambient air temperature changes.

Heat exchangers, inside which the big air volume are contained, have long time constants compared with rotating components like compressors and turbines, and resultantly such measures as incorporating big discharge valves, should be necessary for the normal and emergency shutdown processes, unless otherwise ICAD GTs are difficult to stop safely.

Further analyses, therefore, for further gas-steam cycle GT cases are to based upon the directly intercooled GT (WI) as a base GT.

3.2 MIXED GAS-STEAM CYCLE GT

The resultant performance particulars are listed in Table 2, and the its transfer matrix listed in the lower half of the table, where any parameters are controlled by ambient and operating parameters, are calculated in Excel or Lotus 1-2-3 tabular calculation software by using indices listed in the upper half.*5

The heat balance and temperature variation in this Heat Recovery Steam Generator is shown in Table 3 and in Fig. 7.

In order to settle the performance particulars of mixed gas-steam cycle GT, the iterative calculations are indispensable. The several iterations, at least, are needed to coincide both steam injection indices values and PWT exhaust flow rates/property values in Table 2 & 3 (highlighted in underlined block-type indications). Both GT and HRSG are mutually influential in relation with flow rates and property values, as steam evaporation rates (Table 3) in HRSG are varied by PWT exhaust figures and GT performance values (Table 2) are dependent from steam injection rates, i.e., steam evaporation rates.

WATER-INJECTED ISTIG (WI/ISTIG)

The water, the amount of which is settled to the dew point, is injected at the exit of LPC. It should be noted that the cooled temperature (T25) would be changeable in variation with the LPC discharge pressure, raised by the water injection.

The flow diagram of this intercooled gas turbine cycle is shown in Fig. 2, where the purely treated water is injected at LPC exit. The rated HPT inlet temperature is kept as same 1620 K as settled for the above-intercooled GTs.

Configuration	1% Smaller HPT and 9% Smaller PWT Nozzles
Operation Mode	Water Injected(WI)/ISTIG
Power Output	94.0 MW @ GT Coupling
Efficiency	55.6 % @ GT Coupling
Suction Air Flow	158 kg/s (348 lb/s)
Pressure Ratio	41.4
HPT Inlet Temp.	1,620 K (2,457 F)
Water Injection	3.6 kg/s (8.0 lb/s) @ LPC Exit
Intercooled Temp.	302 K (83 F)
Steam Injection	16.3 kg/s (36.0 lb/s) in Total
GT Exit Temp.	658 K (725 F)
HRSG Exit Temp.	430 K (315 F)

WATER-INJECTED GAS3D (WI/GAS3D)

The water is injected as in the WI/ISTIG cycle, where the medium pressure steam (I27) is to be injected at the exit of MP compressor (@ 27), instead of LP turbine inlet (I47 @ 47).

The performance of water injection intercooled GT with steam injection (WI/GAS3D version) is calculated as shown in the followings.

$$dI24/I24 = 1+ \ 4.3/169 = +1.026$$
$$dI27/I27 = 1+2.3/169/1.026 = +1.013$$
$$dI3/I3 = 1+ 15.4/169/(1+0.026+0.013) = +1.088$$
$$dA4/A4 = -0.010$$
$$dI48/I48 = 1+2.9/169/(1+0.026+0.013+0.088) = +1.015$$
$$dA49/A49 = -0.090$$

The resultant specifications are listed as below.

Configuration	9% Larger HPT and 9% Smaller PWT Nozzles
Operation Mode	Water Injected(WI)/GAS3D
Power Output	107.6 MW @ GT Coupling
Efficiency	55.6 % @ GT Coupling
Suction Air Flow	169 kg/s (373 lb/s)
Pressure Ratio	41.9
HPT Inlet Temp.	1,620 K (2,457 F)
Water Injection	4.3 kg/s (9.6 lb/s) @ LPC Exit
Intercooled Temp.	305 K (90 F)
Steam Injection	20.6 kg/s (45.4 lb/s) in Total
GT Exit Temp.	687 K (777 F)
HRSG Exit Temp.	422 K (299 F)

The power curve in variation with ambient air temperature (T2) is shown in Fig. 6. It is seen that WI/GAS3D GT can offer very flat power characteristics with ambient air temperature.

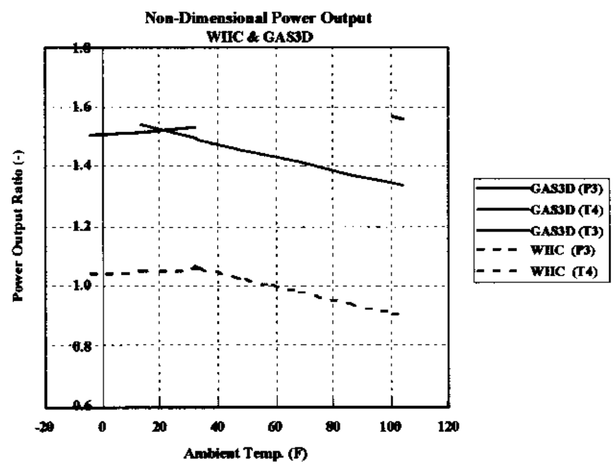

Fig. 6 Power Curve of WI/GAS3D LM6000

GAS3D Cycle	Performance Analysis							**Iw24 (-)**	**0.03**	Tw24(K)	298.2	Cpw24(J/gK)	4.29	Tg24(K)	305.2	Pw24(kPa) 500
Base Engine :	LM6000 Standard/Dry							**Is27 (-)**	**0.01**	Ts27(K)	538.7	Cps27(J/gK)	3.54	Tg27(K)	578.6	Pw27(kPa) 5250
Mode :	1620	K GAS3D/Full WI						**Is3 (-)**	**0.09**	Ts3 (K)	667.0	Cps3 (J/gK)	2.54	Tg3 (K)	752.0	Pw3 (kPa) 7875
Modification:	Free PT	dA49/A=	-0.13	dA47/A=	-0.02	dA4/A4=	0.13	**Is42 (-)**	**0.00**	Ts42(K)	667.0	Cps42(J/gK)	2.54	Tg42(K)	1385.7	Pw42(kPa) 7875
Power @GT	(MW)	107.6		Efficiency @GT (%)	55.6			**Is46 (-)**	**0.00**	Ts46(K)	538.7	Cps46(J/gK)	3.54	Tg46(K)	1195.6	Pw46(kPa) 5250
Fuel Flow	(t/Hr)	15.8						**Is48 (-)**	**0.02**	Ts48(K)	513.5	Cps48(J/gK)	2.80	Tg48(K)	1105.1	Pw48(kPa) 2625

St.	Design'tn	Temp.	Press.	Flow	Gas Cp.	Mixed Cp.	St'm Cp.	S**	m**	K**	f**	h**	g**	L**	N**	HN**
(-)	(-)	(K)	(kPa)	(kg/s)	(kJ/kg/K)	(kJ/kg/K)	(kJ/kg/K)	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)
2	LPC Inlet	288.2	97.3	169.3	1.00	1.00	1.86	0.86	0.33	4.93	1.64		0.13	0.04	-8.39	
24	LPC Exit	361.5	192.3		1.01	1.01	1.89	0.87								
25	MPC Inlet	305.2	184.6	173.6	1.00	1.03	1.87	0.81	0.31	2.11	0.65		0.04	-0.18	-6.07	
27	MPC Exit	579.6	1486.8		1.05	1.07	2.00	0.87								
28	HPC Inlet	578.6	1486.8	165.3	1.05	1.08	2.00	0.85	0.30	3.88	1.15		0.05	-0.07	-0.13	
3	HPC Exit	779.8	4073.8		1.09	1.13	2.14	0.89								
34	COB Inlet	752.0	4073.8	129.0	1.09	1.21	2.12	0.75		1.72	0.72		1.75	-0.15	-0.27	
4	COB Exit	1792.3	3870.1		1.34	1.50	2.75	0.83								
41	HPT Inlet	1545.5	3870.1	163.4	1.32	1.46	2.63	0.80	0.22	8.68	1.86	0.89	1.80	-0.63	-1.15	1.23
42	HPT Exit	1385.7	2327.7		1.30	1.44	2.54	0.77								
44	MPT Inlet	1385.7	2327.7	163.4	1.30	1.44	2.54	0.77	0.21	6.29	1.33	0.90	1.77	-0.52	-0.92	1.34
46	MPT Exit	1195.6	1155.2		1.26	1.39	2.42	0.74								
47	LPT Inlet	1167.6	1155.2	184.2	1.26	1.39	2.41	0.73	0.21	24.19	5.00	0.90	1.73	-0.55	-0.96	1.33
48	LPT Exit	1121.2	949.7		1.25	1.38	2.37	0.73								
49	PWT Inlet	1105.1	949.7	194.3	1.25	1.39	2.36	0.70	0.22	1.64	0.35	1.35	1.70	-0.54	-0.94	1.34
8	PWT Exit	**686.8**	103.9	**194.3**	1.14	**1.26**	2.07	0.65								
92	HPE Exit	581.5	103.4	194.3	1.11	1.22	2.00	0.64								
94	MPE Exit	544.3	102.9	194.3	1.10	1.21	1.98	0.63								
96	IPE Exit	510.6	102.3	194.3	1.09	1.20	1.96	0.63								
98	LPE Exit	481.4	101.8	194.3	1.09	1.19	1.94	0.63								
am	HRSG Exit	421.7	101.3	194.3	1.07	1.18	1.91	0.63								

Ps24 (kPa)	4.7	Tsv24(K)	414.9
SatTs25(K)	305.2	Tsv27(K)	523.5
		Tsv3 (K)	548.7
		Tsv42(K)	548.7
		Tsv46(K)	523.5
		Tsv48(K)	485.7
		Cpsv24(J/gK)	2.25
		Cpsv27(J/gK)	3.79
		Cpsv3 (J/gK)	4.59
		Cpsv42(J/gK)	4.59
		Cpsv46(J/gK)	3.79
		Cpsv48(J/gK)	3.03

	dP2/P2	dT2/T2	dI24/I24	dI27/I27	dI3/I3	dA4/A4	dT4/T4	dI42/I42	dA44/A44	dI46/I46	dA47/A47	dI48/I48	dA49/A49	dP8/P8
dP24/P24	1	-0.61	1.05	1.05	1.05	0.146	0.61	0.69	0.00	0.66	-3.54	-4.55	3.40	0
dP27/P27	1	-1.84	9.80	3.24	3.24	0.441	1.84	2.15	-2.65	-2.70	0.55	-2.21	1.66	0
dP3 /P3	1	-2.20	12.40	2.42	3.92	-1.497	2.20	-0.89	-0.12	-1.99	0.48	-1.52	1.14	0
dP42/P42	1	-2.20	12.40	2.42	3.92	-0.377	2.20	0.62	-1.24	-1.99	0.48	-1.52	1.14	0
dP46/P46	1	-2.20	12.40	2.42	3.92	-0.377	2.20	0.62	-0.13	-0.51	-0.63	-1.52	1.14	0
dP48/P48	1	-2.20	12.40	2.42	3.92	-0.377	2.20	0.62	-0.13	-0.51	0.48	-0.03	0.02	0
dT24/T24	0	0.80	0.35	0.35	0.35	0.049	0.20	0.23	0.00	0.22	-1.18	-1.51	1.13	0
dT25/T25	0	0.80	-5.72	0.35	0.35	0.049	0.20	0.23	0.00	0.22	-1.18	-1.51	1.13	0
dT27/T27	0	0.42	-3.03	1.02	1.02	0.139	0.58	0.68	-0.82	-0.81	0.08	-0.80	0.60	0
dT28/T28	0	0.42	-3.03	0.89	1.02	0.139	0.58	0.68	-0.82	-0.81	0.08	-0.80	0.60	0
dT3 /T3	0	0.31	-2.26	0.65	1.22	-0.435	0.69	-0.22	-0.07	-0.60	0.06	-0.59	0.44	0
dT44/T44	0	0	0	0	0	0.24	1	-0.60	-0.24	0	0	0	0	0
dT47/T47	0	0	0	0	0	0.24	1	-0.60	-0.01	-0.64	-0.24	0	0	0
dT49/T49	0	0	0	0	0	0.24	1	-0.60	-0.01	-0.64	-0.01	-0.63	-0.23	0
dT8/T8	-0.22	0.47	-2.66	-0.75	-0.83	0.561	0.53	-0.83	-0.04	-0.54	-0.11	-1.54	-0.24	0.22
dG2/G2	1	-2.20	11.20	0.93	2.42	-0.497	1.70	-0.89	-0.12	-1.99	0.48	-1.52	1.14	0
dG3/G3	1	-2.20	12.20	1.93	2.42	-0.497	1.70	-0.89	-0.12	-1.99	0.48	-1.52	1.14	0
dG49/G49	1	-2.20	12.20	1.93	3.42	-0.497	1.70	0.11	-0.12	-0.99	0.48	-0.52	1.14	0
dXlc/Xlc	0	0	-2.17	0.86	0.86	0.12	0.5	0.56	0.00	0.54	-2.91	-3.73	2.79	0
dXmc/Xmc	0	0	0.39	0.89	0.89	0.12	0.5	0.59	-0.86	-0.98	0.74	0	0	0
dXhc/Xhc	0	0	0.40	0.40	0.90	-1.043	0.5	-1.40	1.04	0	0	0	0	0
dHP/HP	1.35	-2.98	17.39	4.01	5.53	-0.784	3.48	0.68	-0.07	-1.09	0.65	1.05	0.91	0.35
dWf/Wf	1	-2.43	14.65	2.31	3.49	-0.183	2.93	1.05	-0.08	-0.83	0.44	-0.39	0.82	0
dQP/QP	-0.35	0.55	-2.74	-1.70	-2.05	0.601	-0.55	0.37	-0.01	0.25	-0.21	-1.44	-0.10	-0.35

Table 2 Performance Particulars and Transfer Matrix of WI/GAS3D Mode Gas Turbine

GAS3D Cycle Performance Analysis			Heat Recovery Steam Generator						
	Base Engine:	LM6000 Standard/Free PT						**Iw24 (-)**	**0.026**
	Modificat'n:	Free PT						**Is27 (-)**	**0.013**
	Mode :	1620.2	K ISTIG/Full WI					**Is3 (-)**	**0.088**
	dA49/A=	-0.13	dA47/A=	-0.02	dA4/A4=	0.13		**Is42 (-)**	**0**
	GT Inlet	Gas Flow	169.3					**Is46 (-)**	**0**
	LPC Exit	Water Flow	0.026					**Is48 (-)**	**0.015**
	GT Exhaust	Gas Flow (kg/s)	**194.3**	Gas Temp. (K)	**686.8**	Gas Sp.Cp. (kJ/kg/K)	**1.26**		
		Gas Flow (kg/s)	Gas Temp. (K)	Gas Cp. (kJ/kg/K)	St'm Flow (kg/s)	St'm Temp. (K)	St'm Cp. (kJ/kg/K)	Latent H't (kJ/kg)	St'm Pres. (kPa)
0	HP Sphtr Exit	**194.3**	**686.8**	**1.26**	15.4	672.0	2.49		6000
0.5	HP Evptr Exit	194.3	659.3	1.25	15.4	548.7	4.59	1571	6300
2	HP Evptr Inlet	194.3	558.7	1.24	15.4	548.7	5.08		6300
4	IP Sphtr Exit	194.3	558.7	1.24	2.3	543.7	3.35		4000
4.5	IP Evptr Exit	194.3	558.0	1.24	2.3	523.5	3.78	1713	4200
6	IP Evptr Inlet	194.3	533.5	1.23	17.7	523.5	4.86		4200
6	LP Sphtr Exit	194.3	533.5	1.23	2.9	518.5	2.67		2000
6.5	LP Evptr Exit	194.3	532.3	1.23	2.9	485.7	3.03	1888	2100
8	LP Evptr Inlet	194.3	495.7	1.22	20.6	485.7	4.53		2100
8	Ecnzr Inlet	194.3	495.7	1.22	20.6	480.7	4.53		2100
10	Ecnzr Inlet	194.3	421.7	1.19	20.6	298.2	4.53		2100

Table 3 HRSG Heat Balance of WI/GAS3D GT

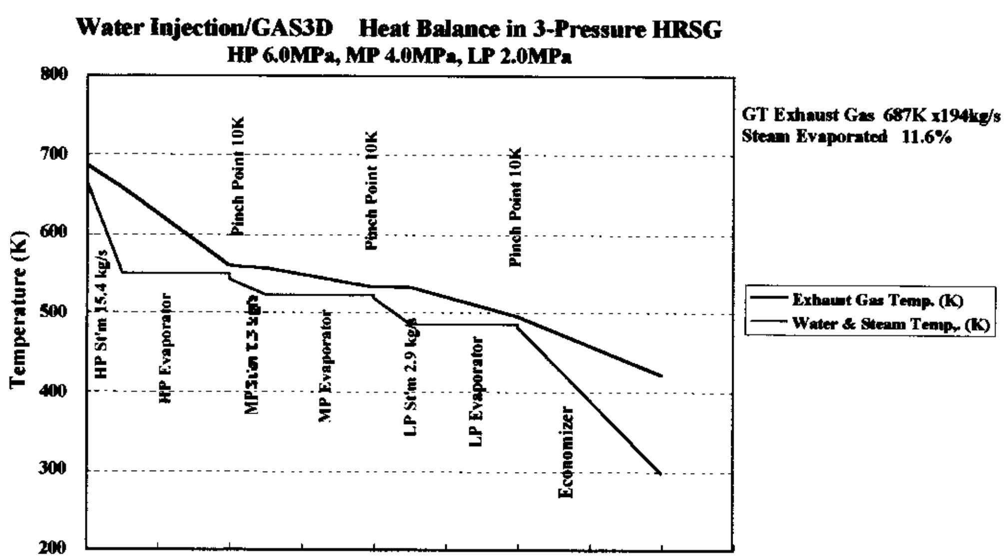

Fig. 7 HRSG Heat Balance of WI/GAS3D GT

4. EVALUATION OF STUDY RESULTS

MIXED GAS-STEAM CYCLE GT

It can be seen in Fig. 8 that any injected water/steam cycles are subject to very high temperature-based Rankine Cycle, of which the maximum cycle temperature is very same as main gas temperature. This would be one of main reasons for offering better resultant efficiency than those in conventional combined cycles. The ISTIG or GAS3D cycle is not of conventional combined cycle type, from view points of mechanical definitions, which is of dual-fluid cycle type, combined thermodynamically inside.

The "Brayton" Cycle of 1600 K maximum temperature brings about thermal efficiency of 42 %, and, on the contrary, the "Rankine" Cycle of 700 K maximum temperature, which would be appropriate for the bottoming cycle, may have 30 % efficiency at best. Accordingly, it might be anticipated that it is better for the evaporated steam to be used in much higher "Rankine" Cycle of 40% due to 1600K steam.

Such high "Rankine" Cycle efficiency of back-pressure type, could contribute the very flat power characteristics in variation with ambient temperature, because of the excellent recovery from GT exhaust heat to be anticipated bigger in hot seasons, compared with the steep power curve due to the moderate recovery by the bottoming cycles in conventional combined cycle plants.

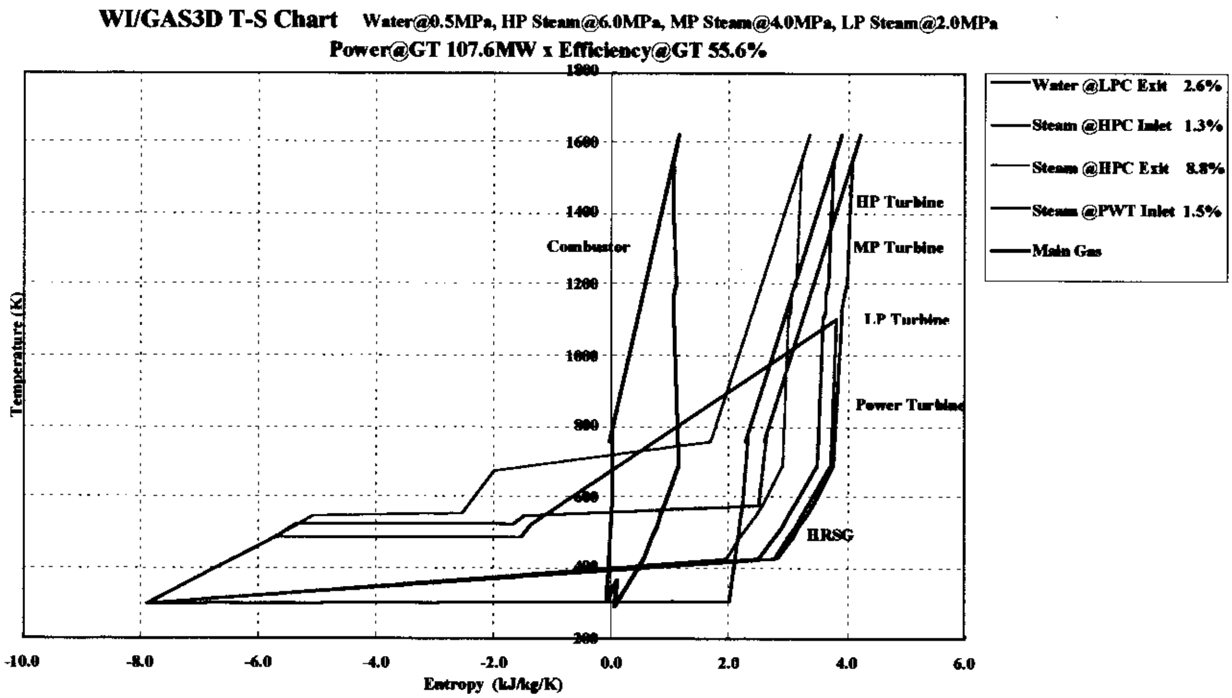

Fig. 8 Gas & Steam T-S Diagram of a WI/GAS3D GT

TURBINE NOZZLE AREA CHANGES

When injecting steam into the turbine gas flow, it is normal that the turbine inlet pressure has to be increased to maintain the corrected gas flow as constant, corresponding to the speed-up of rotating speed. These two parameters, i.e., P41 (HPT inlet pressure) and Xhc (HPT spool speed), are very important factors for making decision of the gas turbine life, to limit thrust bearing capacity and mechanical strength of rotating parts. Not to increase these two parameters, the enlargement of the turbine nozzle area with the adjustment of turbine nozzle setting angle is to be considered.

It was acknowledged in case studies that the countermeasure of enlarging the nozzle areas is very useful to avoid the speed increase when injecting steam/water into the gas turbine without any sacrifices of the performance parameters or sometimes with better performance. It would not be so difficult to adjust the nozzle area within the range of plus or minus 10 %, by rotating the setting angle of nozzle cascade rows with buckets as it is.

5. CONCLUSIONS

ISTIG/GAS3D gas turbine cycles could be counted as an excellent cycle improvement ideas. The assumed limits, i.e., 1620 K (2467 F) for TIT (T4) and 42 for CDP pressure ratio (P3/P2), yields in the results of 107 MW capacity with 56% LHV efficiency at GT coupling. And this kind of mixed gas-steam cycle is of much more flexible operability with or without water/steam injection, and is capable to continue running dry GT even in the case of steam line troubles. Also these cycle plants can offer much faster load change capability by incorporating quick steam governor valves in addition to the normal fuel gas governor, comparing with conventional combined cycle plants.

1) More Power Output in a Hot Season
The following figure is the power variation characteristics of GAS3D cycles under P3, T4, and T3 control, comparing with the very steep power curve of dry GT under T3 control, i.e., 5.4% power losing by 1% ambient temperature rise.
It can be seen that GAS3D GT has very flat curve, i.e., only 1.4% power decrease by 1% ambient air temperature increase, and T3 control parameter is already meaningless for GAS3D, which is most important control parameter for Dry GT at high ambient temperature region.

Although so-called "HAT" cycle with the big air saturator prior to the combustor has an almost horizontal power characteristics against the ambient air temperature change by more effective latent heat usage, it can be said that GAS3D cycle could offer excellent power output in a hot season.

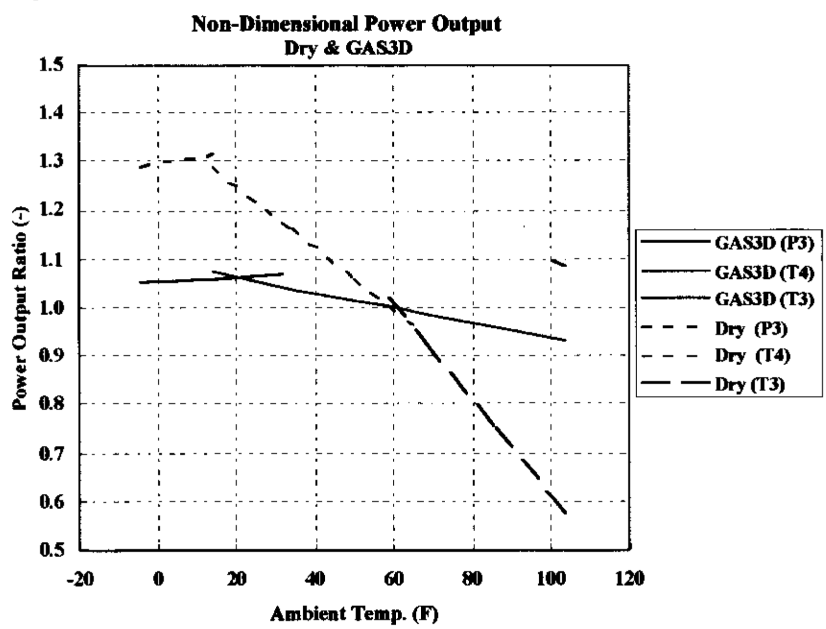

Fig. 9 Power Characteristics of Dry and GAS3D Cycle GTs

2) Feasibility on ISTIG/GAS3D Cycle
ISTIG/GAS3D might be superior to other cycle improvement ideas such as "Kalina-Cycle", "H-Technology" etc, especially from viewpoints of better power capability in hot seasons.
Some features are summarized:
- Unnecessary to have a bottoming cycle components, saving a lot of investment related to the equipment of a bottoming cycle.
- Better resultant plant efficiency by much higher steam maximum cycle temperature of 1600 K (2400 F) class, mixed in the advanced efficient gas turbine.
- Capable of quick load changes and stop sequence without any special measures, due to no heat exchangers of big time constants in the main air/gas stream.

3) Applicability of Aero-Derivative GT into ISTIG/GAS3D Cycle
It is confirmed that 56% thermal efficiency with the flat power curve characteristics is attained in GAS3D Cycle, based upon the directly intercooled LM6000GT(WI) as a base GT.

And it would be expected to exceed 60 % level by applying up-rated version of existing LM6000 or equivalent GTs, which have to have much bigger pressure ratio than existing 2.4 levels at LPC.

When applying this ISTIG/GAS3D cycle to the advanced GT like GE90, Trent800, and PW4000 derived GTs, it is easy to get 62% thermal efficiency generating plant with very flat power curves against the air temperature change.

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