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Integration of steam injection and inlet air cooling for a gas turbine generation system

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Abstract

The temperature of exhaust gases from simple cycle gas turbine generation sets (GENSETs) is usually very high (around 500 °C), and a heat recovery steam generator (HRSG) is often used to recover the energy from the exhaust gases and generate steam. The generated steams can be either used for many useful processes (heating, drying, separation etc.) or used back in the power generation system for enhancing power generation capacity and efficiency. Two well-proven techniques, namely steam injection gas turbine (STIG) and inlet air cooling (IAC) are very effective features that can use the generated steam to improve the power generation capacity and efficiency.

Since the energy level of the generated steam needed for steam injection is different from that needed by an absorption chiller to cool the inlet air, a proper arrangement is required to implement both the STIG and the IAC features into the simple cycle GENSET.

In this study, a computer code was developed to simulate a Taipower's Frame 7B simple cycle GENSET. Under the condition of local summer weather, the benefits obtained from the system implementing both STIG and IAC features are more than a 70% boost in power and 20.4% improvement in heat rate.

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Keywords: Gas turbine; Steam injection; Inlet air cooling; Absorption chiller

1. Introduction

The power generation systems driven by simple cycle gas turbine engines require relatively small footprint areas and possess quick startup and shutdown capabilities. Many simple cycle

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Nomenclature

COP	coefficient of performance
$\dot{E}$	exergy rate, kW
$\dot{E}_{\mathrm{D}}$	exergy destruction rate, kW
$\dot{E}_{\mathrm{R}}$	exergy recovered rate, kW
$\dot{E}_{\mathrm{S}}$	exergy supplied rate, kW
h	specific enthalpy, $\mathrm{kJ\,kg^{-1}}$
LHV	low heating value, $\mathrm{kJ\,kg^{-1}}$
$\dot{m}$	mass flow rate, $\mathrm{kg\,s^{-1}}$
$\dot{Q}$	heat transfer rate, kW
r	compression ratio
T	temperature, K
TIT	turbine inlet temperature, K
T_0	ambient temperature, K
x	steam injection ratio
$\dot{W}$	work rate, kW
ε	exergy efficiency
η_{g}	power generation efficiency

Subscripts

1–16	state point
a	air
cv	control volume
des	desorber
e	exit
evap	evaporator
f	fuel
i	inlet
k	kth component
l	liquid water
q	heat transfer
v	vapor

generation sets are, thus, used by Taipower (Taiwan Power Company) to serve as peak load units, which can be started quickly but suffer from very low efficiency, especially during summer peaking hours when electricity is most needed. To mitigate the anticipated power shortage, retrofitting projects have been seriously considered to convert these existing simple cycle gas turbines into more advanced cycle units with higher efficiency and higher power output.

The thermodynamic processes of a simple cycle gas turbine can be approximately modeled as a Brayton cycle, in which the back work ratio is usually very high, and the exhaust temperature is often above 500 °C. A high exhaust temperature implies there is plenty of useful energy wasted to the environment. The recovery of this otherwise wasted energy can be used to improve either the power generation capacity or/and efficiency [1–3] via modifications to the basic cycle, such as gas to gas recuperation [4], steam injection [5], evaporation cycle [6], chemical recuperation [7], inlet air cooling (IAC) [8] and combined cycle [9,10].

Among many well-proven technologies, the combined cycle is perhaps the most popular way to recover the energy from the exhaust gas, and the recovered energy is actually used to boost the capacity and efficiency of power generation. For a combined cycle, the compatibility between the top cycle (gas turbine cycle) and the bottom cycle (steam turbine cycle) is important to its overall performance, and its mobility (start up time) is relatively low. The combined cycle is, therefore, unsuitable for our projected unit, in which the daily on–off operation pattern is required.

Among many other technologies, the steam injection gas turbine (STIG) and IAC also have become common practices to enhance the performance of power generation. Both features are very cost effective and can be implemented in the basic system without major modification to the original system integration.

The STIG method stands for steam injected gas turbine. The steam generated from the heat recovery steam generator (HRSG) is injected into the combustion chamber. Air from the compressor and steam from the HRSG both receive fuel energy in the combustion chamber and both expand inside the same turbine to boost the power output of turbine. It should be noted that the required pressure of the injected steam is obtained from a pump. Since the pumping work is 2–3 orders of magnitude smaller than that of the compressor, the net power output produced by steam is, thus, much higher than that of air in terms of per unit mass flow rate. In addition, the specific heat of superheated steam is almost double the value of air and the enthalpy of steam is higher than that of air at a certain temperature. Therefore, the STIG method is a very effective way to boost the net power output and increase the overall efficiency of gas turbines. In fact, STIG has become a well established practice [11]. Tuzon [12] also reported the development of STIG technology, including a list of turbines for conversion. Recently, Swanekamp [13] also reported the Cheng Power System successfully implemented Frame 6B simple cycle GENSETs.

The use of compressor IAC to compress more air per cycle to increase the capacity of the gas turbine has also been widely accepted [14]. The study by Lucia [15] has allowed the designer to recognize the benefits and limitations and to assist in successful design and implementation of IAC systems. Different options (including evaporative cooling, mechanical chiller, absorption chiller and thermal energy storage) in gas turbine power augmentation using IAC were discussed comprehensively by Ondryas [16]. Among these, recovering the waste heat to generate steam that, in turn, powers an absorption chiller is naturally matched with the use of STIG. Use the same HRSG to recover most of useful energy and generate as much steam as possible, the high pressure steam being injected into the combustor and the lower pressure steam being used to power the absorption chiller.

Although many efforts have been devoted to either apply the STIG technology or the IAC method to enhance gas turbine performance [17,18], to our knowledge, none have ever integrated STIG and IAC for the same system. Since the energy levels required by IAC and STIG are different, the recovered energy could be more fully utilized by a combined STIG and IAC system. The degree of improvement can be further enhanced if the condensate from the IAC cooler can be used to supplement the cooling water for the absorption chiller and the used cooling water (already heated) from the absorption chiller can, in turn, be used as the feed water for the HRSG.

In this study, an actual simple cycle generation unit is considered as base unit, and STIG and IAC features are sequentially added to the system. The benefits obtained from either the STIG or IAC can be distinguished, and the integration effects from the combined STIG and IAC can be realized.

2. System description

A simple cycle GENSET of Taipower is considered as the base unit. The rated output of this unit under ISO condition (101.3 kPa, 288 K, 60% RH) is 60.3 MW if natural gas is used and is 59.0 MW if distillate oil is used. Several major design specifications of this unit are presented in Table 1, in which the exhaust temperature is 783 K (510 °C). This means there is a plenty of useful energy expelled to the atmosphere.

In order to recover this otherwise wasted energy, a HRSG is installed, see Fig. 1, to recapture most of this energy and generate steam with pressures suitable either for an absorption chiller or/and for a steam injection system.

The maximum energy that can be recovered by the HRSG is limited by the effectiveness of the HRSG and the outlet temperature of the flue gas. The effectiveness of the HRSG is set to be 0.8, and the exhaust temperature from the stack (point 5 in Fig. 1) is set to be 393 K (120 °C) to prevent the possibility of vapor condensation.

A typical absorption chiller with the capacity rated at 3300 refrigeration tons is used to cool the chilling water, which, in turn, is used to cool the inlet air of the power generation system. Since the working fluid of the absorption chiller is a lithium bromide (LiBr) solution, the evaporator temperature is about 277 K (4 °C). This temperature limits the minimum temperature of the inlet air, which cannot be lower than 283 K (around 10 °C).

Table 1
Typical operating parameters used in the retrofitted system

Turbine inlet temperature	1264 K
Ambient temperature	305 K
Compressor efficiency	0.86
Turbine efficiency	0.87
Generator efficiency	0.98
Compression pressure ratio	9:1
Mass flow rate of air	221.28 $kg\,s^{-1}$
LHV of fuel	802,361 kJ/kmol
Chemical exergy of fuel	824,348 kJ/kmol
Pressure of injected steam	1.41 MPa
Pressure of injected fuel	1.70 MPa
Pressure loss of combustor/HRSG	5%
Pressure loss of compressor/turbine	1%
Desorber inlet temperature of absorption chiller	393 K
Desorber inlet pressure of absorption chiller	0.2 MPa
Supply chilling water temperature of absorption chiller	285 K
Return chilling water temperature of absorption chiller	280 K
Supply cooling water temperature of absorption chiller	305 K

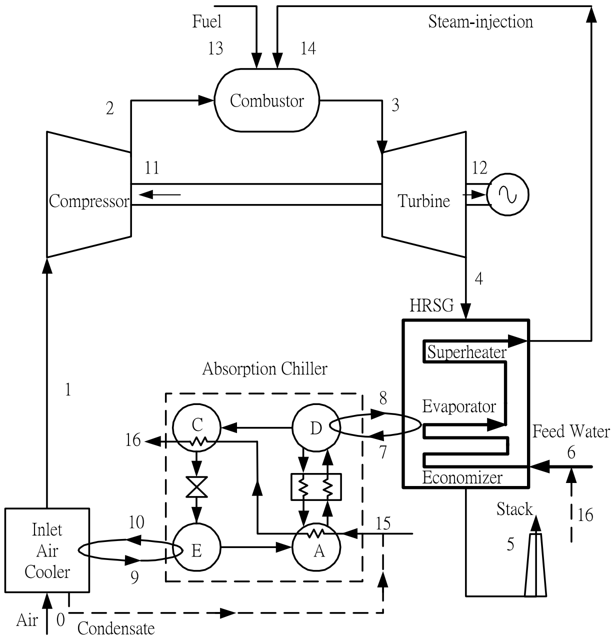

Fig. 1. Schematic diagram of the retrofitted system.

The total heat required by the absorption chiller to cool the compressor inlet air to the temperature of 10 °C is only a small fraction of the available exergy which can be obtained from the turbine exhaust gases. In order to utilize fully the recoverable energy, the STIG mechanism was also implemented in the system. In other words, a two pressure HRSG will be used to recover the waste heat and generate the required steams. Low pressure steam (at 0.2 MPa) is used to heat the desorber (component D in Fig. 1) of the absorption chiller, and high pressure steam (at 1.41 MPa) is directly injected into the combustor, see the state points 7 and 14 in Fig. 1.

The drain pan under the inlet cooler will collect a great quantity of condensate under hot and humid weather conditions. The temperature of this condensate is slightly lower than the temperature of the inlet air. Since the COP of the absorption chiller will be increased as the cooling water temperature is decreased, see Fig. 2, this low temperature condensate (about 10 °C) is used to supplement the cooling water for the absorber (component A) of the absorption chiller, see point 15 in Fig. 1.

After passing through the absorber, the cooling water (at about 36 °C) will sequentially be used to cool the condenser (component C) of the absorption chiller. The cooling water leaving the condenser at about 39 °C will usually release its heat to ambient via a cooling tower. In the present study, part of the cooling water from the condenser (state point 16) is used as the feed water of the HRSG (state point 6). By this arrangement, the temperature of the feed water can be elevated (preheated) about 7 K, which implies more useful steam can be generated. In addition, the capacity (size) of the cooling tower and the water evaporated by the cooling tower (to release the latent heat) can be reduced.

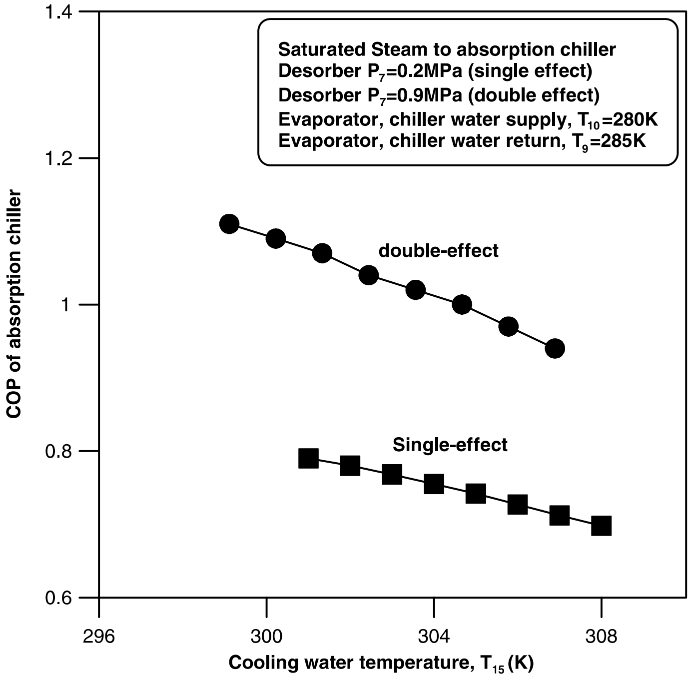

Fig. 2. The effect of cooling water temperature on COP of absorption chiller.

3. Thermodynamic modeling and computer simulation

A computer program was developed by us to simulate successfully the gas turbine generation system [19,20], in which the control volume model of each component was constructed using mass, energy and exergy balances for determining the thermodynamic properties at every key position in Fig. 1. A set of governing equations for a particular component (k) is expressed as:

mass rate balance

$$\sum_{\mathrm{i}} \dot{m}_{\mathrm{i},k} = \sum_{\mathrm{e}} \dot{m}_{\mathrm{e},k} \tag{1}$$

energy rate balance

$$\dot{Q}_{\mathrm{cv},k} - \dot{W}_{\mathrm{cv},k} = \sum_{\mathrm{e}} \dot{m}_{\mathrm{e},k} h_{\mathrm{e},k} - \sum_{\mathrm{i}} \dot{m}_{\mathrm{i},k} h_{\mathrm{i},k} \tag{2}$$

exergy rate balance

$$\dot{E}_{\mathrm{D},k} = \sum \dot{E}_{\mathrm{q},k} - \dot{W}_{\mathrm{cv},k} + \sum_{\mathrm{i}} \dot{E}_{\mathrm{i},k} - \sum_{\mathrm{e}} \dot{E}_{\mathrm{e},k} \tag{3}$$

where $\dot{E}_{\mathrm{D}}$ denotes the rate of exergy destruction and $\dot{E}_{\mathrm{q}}$ denotes the associated exergy transfer rate due to heat transfer.

If the effects of kinetic and potential are ignored, the total exergy rate $\dot{E}_k$ consisting of physical exergy and chemical exergy can be expressed as [24]

$$\dot{E}_k = \dot{E}_k^{PH} + \dot{E}_k^{CH} \tag{4}$$

where the physical exergy and chemical exergy of air, fuel and water can be found in the Appendix of Ref. [21]. The chemical exergy of the gases mixture is obtained by summing the overall compositions of air, that includes N_2, O_2, CO_2, $H_2O_{(g)}$ and other gases.

It was assumed that the retrofitted system operated at steady state, and the ideal gas mixture models apply for air/steam and combustion products. The combustion in the combustor is complete. All components are adiabatic except that the combustor exhibits a heat loss at 2% of the LHV. The pressure losses in each component are listed in Table 1, and the effects due to kinetic and potential energies are ignored.

The system of the absorption chiller driven by low pressure steam of the HRSG was simulated by the ABSIM code, a modular code developed under DOE/ORNL sponsorship. The code has been employed successfully to simulate a variety of absorption chillers (single effect, double effect, using different working fluid pairs) [22].

The heat energy available in the form of steam generated by the HRSG to the desorber of the absorption chiller cycle can be calculated as

$$\dot{Q}_{des} = \dot{m}_4(h_4 - h_5) - \dot{m}_6(h_{14} - h_6) \tag{5}$$

The COP of the absorption cycle is defined as the ratio of the evaporator cooling capacity to the desorber heating load

$$COP = \frac{\dot{Q}_{evap}}{\dot{Q}_{des}} \tag{6}$$

Actual manufacturer catalog data were used as inputs for the ABSIM code. Both single effect and double effect systems were simulated in this study. To simplify the description, only the single effect parameters are presented in this study.

The inlet air cooler is an indirect type air to water heat exchanger. It is assumed that the water vapor in the air will be condensed, the condensed water is drained and air with 100% RH is supplied to the compressor. Through the conservation laws of air/vapor and chilled water, the heat transfer rate per unit air flow rate can be calculated as

$$\frac{\dot{Q}_{iac}}{\dot{m}_{a1}} = (h_{a1} + \omega_1 h_{v1}) - (h_{a0} + \omega_0 h_{v0}) + (\omega_0 - \omega_1)h_{l1} \tag{7}$$

where the subscripts a, v, l denote the dry air, vapor and liquid water, respectively, while 0 and 1 denote the state points of the inlet and output of the air cooler. The humidity ratio ω is defined as $\omega = \dot{m}_v/\dot{m}_a$. The transmission loss between the inlet air cooler and the absorption chiller was assumed to be 3%, and the by pass factor of the air cooling coil was assumed to be 0.85. The flow rate of water condensate can be calculated by

$$\dot{m}_{l1} = \dot{m}_{a1}(\omega_0 - \omega_1) \tag{8}$$

All the psychrometric properties of the air/vapor mixture were calculated using the computerized sub-program, which were incorporated into our developed gas turbine simulation program.

The power generation efficiency η_g is defined as

$$\eta_g = \frac{\dot{W}_{net}}{\dot{m}_f(\mathrm{LHV})} \tag{9}$$

Since the exergy efficiency (ε) can provide the true measure of energy loss, which cannot be properly obtained from the energy viewpoint, the exergy efficiency of the components can be expressed in a general form

$$\varepsilon = \frac{\dot{E}_R}{\dot{E}_S} = \frac{\dot{E}_R}{\dot{E}_R + \dot{E}_D} \tag{10}$$

where $\dot{E}_S$ is the exergy rate supplied to the component, $\dot{E}_R$ is the exergy rate recovered from the component and $\dot{E}_D$ is the exergy destruction rate of the component.

4. Results and discussion

In the preliminary study, the accuracy of our developed computer program was validated by simulating the basic Frame 7B simple cycle generation set under ISO conditions (101 kPa, 288 K, 60% RH). The performance data and conditions of this unit were provided by Taipower's Ta-Lin power plant. At the rated turbine inlet temperature (1264 K), exhaust temperature (783 K), compression ratio (9.0) and the flow rate of inlet air at 238.89 (kg s^{-1}), the calculated power output and power generation efficiency were 60.32 MW and 31.04%, which are very close to the rated values of 60.35 MW and 31.05%, see Fig. 3. In this simulation, the efficiencies of the compressor and turbine were adjusted to be 0.86 and 0.87, respectively. These values are quite reasonable and are used for the following calculations.

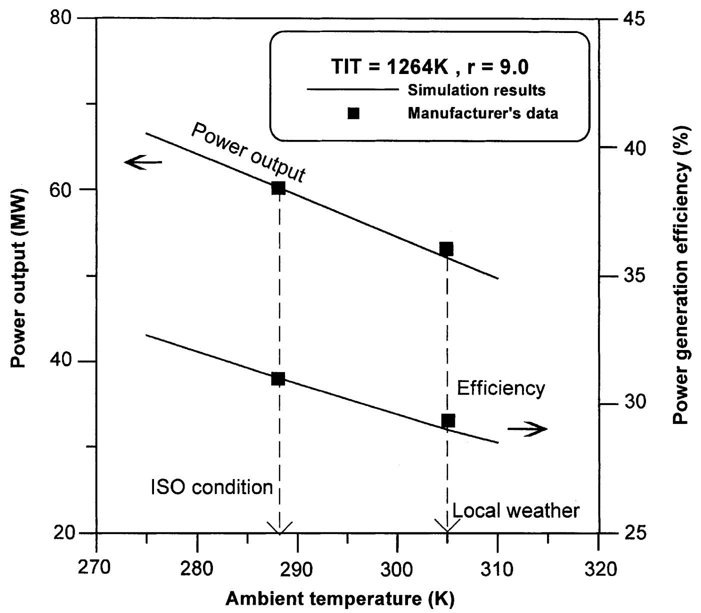

Fig. 3. Effect of ambient temperature on power output and generation efficiency.

Fig. 3 also shows the calculated power output and generation efficiency both decline under higher ambient temperature. At the summer average temperature of 305 K, the power output decreased by approximately 13.5% from the ISO rating (from 60.3 to 52.14 MW), and the efficiency of power generation declined from 31.04% to 29.1%, which also showed good agreement with the manufacturer's data. From the results of Fig. 3, the benefits that are expected to be obtained from the inclusion of the IAC feature is about 12% increase in power output and 5.16% increase in efficiency when the ambient temperature is cooled from 305 to 283 K (the limiting inlet temperature in this study).

The benefit of adding the STIG feature can be estimated from Fig. 4, in which both the power output and generation efficiency are increased with the increase of injection ratio. The maximum amount of injection steam is limited by the available energy recovered from the HRSG. The maximum injection steam for the frame 7B GENSET is estimated to be around 19% (by mass) of the original gas flow rate passing through the turbine component. The maximum injection ratio at 19% is still below the allowable injection limit for the frame 7B GENSET according to Cheng [23]. From Fig. 4, it is found that the power output can be substantially increased from 52.14 to 85.56 MW, and the associated efficiency can be increased from 29.3% to 37.24% during a typical local summer condition.

Although the amount of steam required by the IAC is only a fraction of the amount that can be generated from the waste energy, the allowable amount of steam that can be injected into the combustor for the STIG feature is more than the maximum remaining amount that can be generated from the waste energy. The calculations were also performed for the system with both the IAC and STIG features.

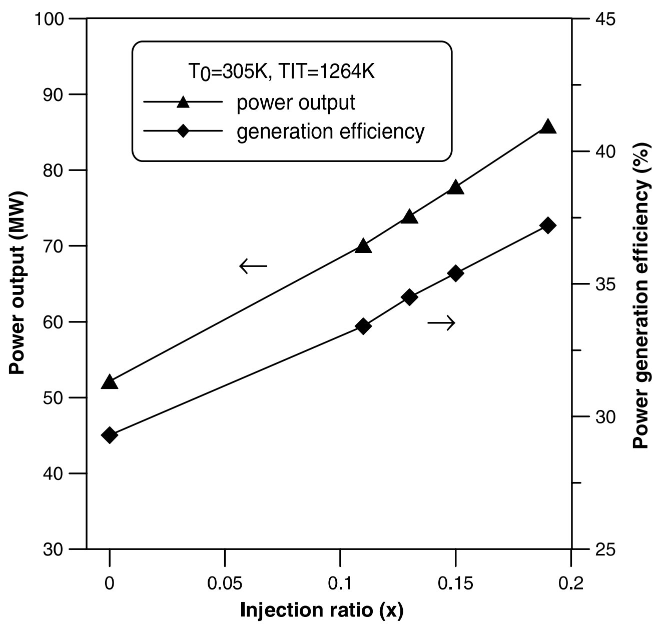

Fig. 4. The effect of injection ratio on power output and generation efficiency.

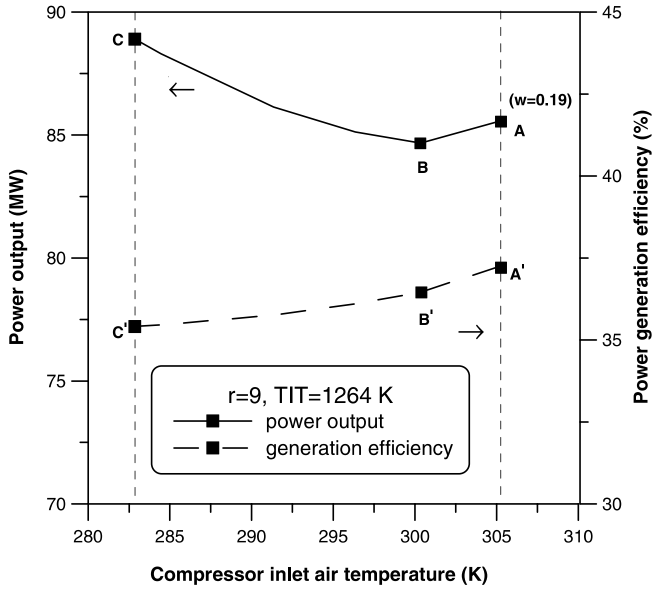

Fig. 5. Performance improvement by steam injection and compressor inlet air cooling.

Fig. 5 shows the results of the system with both the STIG and IAC features. At the maximum injection (point A (A′), all the generated steam is used for the STIG, $w = 0.19$), the power output and efficiency are 85.56 MW and 37.24%, respectively. When some of the generated steam is shared by the absorption chiller, both the output and efficiency drop to 84.67 MW and 36.46%. Point B (B′) represents the state for which the minimum amount of steam (minimum partial load) is required for the absorption chiller to be operated properly. From point B (B′), the power output turns upward until hitting the limiting inlet temperature (283 K) at point C, but the power generation efficiency continues to slide down (very slowly) to 35.41% at point C′.

From the above result, we can discern that the effect of the STIG is more profound than that of the IAC in improving the power output and efficiency. At full injection, the integrated system has the highest efficiency at 37.24% (point A′). At the limiting inlet temperature ($T_1 = 283$ K, $w = 0.13$), the integrated system has the largest output at 88.2 MW (point C).

The exergy destruction rate ($\dot{E}_{\mathrm{D}}$) represents the waste of energy availabilities. Exergy destructions of all the components have been calculated to enhance understanding of the cycle performance. Table 2 shows the exergy destruction rate of each component after retrofitting. In examining the exergy destruction rate for all the components, the combustor has the largest exergy destruction and shows the major site of thermodynamic inefficiency because of the large irreversibilities arising from the chemical reaction and heat transfer. Steam injection will also increase the exergy destruction due to mixing in the combustor. A relative small degree (at 3.57 MW) of exergy destruction also is generated by the absorption chiller because of the chemical absorption/desorption and mixing of the working fluid. However, it is neglectable in comparison with the overall improvement of exergy waste.

The exergy rate at state point 5 (see Fig. 1) is considered as exergy loss through the stack. Because most of the exhaust heat is recovered in the HRSG and used by the STIG and IAC, the

Table 2
Comparisons of thermodynamic performance data after the retrofitting ($T_0 = 305$ K, $r = 9$, TIT = 1264 K)

System	Existing simple cycle		IAC cycle		STIG cycle + IAC	
Power output (MW)	52.14		62.48		88.20	
Power generation efficiency	0.29		0.32		0.35	
Component	$\dot{E}_D$ (MW)	ε	$\dot{E}_D$ (MW)	ε	$\dot{E}_D$ (MW)	ε
Compressor	5.10	0.93	6.49	0.91	6.49	0.91
Combustor	69.38	0.73	75.34	0.74	111.21	0.70
Turbine	7.16	0.88	6.52	0.91	9.08	0.91
HRSG	–	–	15.95	0.37	31.51	0.60
Absorption chiller	–	–	3.57	0.60	3.57	0.60
Inlet air cooler	–	–	0.87	0.67	0.87	0.67
Stack-loss	54.40	–	52.38	–	13.05	–
Total exergy loss $\sum \dot{E}_D$	136.04	–	161.12	–	175.78	–
Per MW loss $\sum \dot{E}_D$/MW	2.61	–	2.58	–	1.99	–

exhaust exergy out of the stack (see Table 2) can be reduced substantially after retrofitting (from 54.4 to 13.05 MW). The exergy losses through the stack will not only waste the available energy but also reflect the degree of thermal pollution to our living environment. The total exergy loss per thermodynamic cycle (the second to last line in Table 2) increases with the addition of the IAC or STIG feature because more components (more reaction processes) will be implemented into the system. However, the modified system has a substantial gain in power output. In terms of exergy loss per MW output, the system with both the STIG and IAC feature is 23.7% lower than that of the basic system, see the last line of Table 2.

5. Conclusions

Steam injection and inlet air cooling are well-proven technologies that can effectively improve power output and power generation efficiency for a simple cycle gas turbine GENSET. In this study, an existing Frame 7B simple cycle GENSET was considered as the basic system and converted into the modified system with either the IAC or/and STIG features. The steam needed in the STIG and IAC features is generated from the energy recovered from the system's own exhaust gases.

Under the average local summer weather, the benefit of adding the STIG feature can substantially improve the power output from 52.14 to 85.56 MW and power generation efficiency from 29% to 37.24%. The maximum power that can be reached by the system with both the IAC and STIG features is 88.2 MW.

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