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Performance improvement for a simple cycle gas turbine GENSET—a retrofitting example

F.J. Wang, J.S. Chiou *

Department of Mechanical Engineering, National Cheng Kung University, Tainan 701, Taiwan, ROC

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Abstract

Due to the serious power shortage in Taiwan, many simple cycle gas turbine generation sets (GENSETs) that were originally designated to serve as peak load units are forced to operate continuously during the entire summer season. The retrofitting projects have been seriously considered to convert these GENSETs (which have the advantage of fast startup, but suffer from low power output and thermal efficiency at high ambient temperature) into more advanced cycle units with higher efficiency and higher output. Among many proven technologies, such as inlet air cooling, intercooling, regeneration, reheating and steam-injection gas turbine (STIG) etc., STIG is found to be one of the most effective in boosting both the output capacity and thermal efficiency. The results from computer simulation indicated that the retrofitting of existing GE Frame 6B simple cycle unit into STIG cycle can boost the output from about 38 to 50 MW, while the generation efficiency can be increased from about 30% to 40%. Besides, the power output of STIG cycle is less sensitive to ambient temperature than that of simple cycle. NO_x reduction to less then 25 ppm (when LNG is used) and operating flexibility under variable heat demand could be achieved. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Retrofitting; Gas turbines; Cogeneration; Steam injection

1. Introduction

In Taiwan, many simple cycle gas turbine generation sets (GENSETs) that were originally designated to serve as peak load units can be started up quickly (usually only takes 15 min), but unfortunately suffer from very low efficiency (around 28%) and reduction in power output during

* Corresponding author. Tel.: +886-6-275-7575x62176; fax: +886-6-208-0383.
E-mail addresses: fjwang@chinyi.ncit.edu.tw (F.J. Wang), jschiou@mail.ncku.edu.tw (J.S. Chiou).

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Nomenclature

$\dot{E}$	exergy rate (kW)
$\dot{E}_D$	exergy destruction rate (kW)
$\dot{E}_R$	exergy recovered rate (kW)
$\dot{E}_S$	exergy supplied rate (kW)
LHV	low heating value (kJ/kg)
$\dot{m}_f$	mass flow rate of fuel (kg/s)
$\dot{Q}_P$	process heat demand (kW)
r	compression ratio
TIT	turbine inlet temperature (K)
T_0	ambient temperature (K)
UF	utilization factor
W	power (kW)
ε	exergy efficiency
x	stream-injection ratio
η_c	compressor efficiency
η_g	power generation efficiency
η_t	turbine efficiency

summer season (when electricity is most needed). To mitigate the anticipated power shortage, retrofitting projects have been seriously considered to convert these simple cycle GENSETs into more advanced cycle units with higher efficiency and higher power output.

Due to a relatively high back-work ratio, the improvement of the net power output for gas turbine is often realized either by reducing the compressor's compression work or by increasing the turbine's expansion work. Since the open gas turbine can be approximately modeled as the Brayton cycle, the efficiency improvement for gas turbine GENSETs were usually focused in three areas: (1) increasing the TIT, (2) increasing the efficiencies of turbo-machinery components, and (3) adding modifications to the basic cycle [1]. Raising TIT may be the most effective way to boost both capacity and efficiency, however, it is usually limited by the material strength to resist heat and by the better cooling technology for some critical parts of turbine. The increased efficiencies of the turbines and compressors should definitely result in an increase in the cycle efficiency, however, the replacement of a delicate rotating component with high speed most likely will face some incompatible problems. The first two ways of the above mentioned efficiency-improvement methods are not quite suitable for a retrofitting project. Our efforts were then concentrated on the modifications to the basic cycle.

An overview about the efficient use of energy by utilizing gas turbine combined systems was recently presented by Najjar [2]. Some advanced gas turbine cycles with heat recovery have been discussed and compared by Heppenstall [3]. Most of these discussions are mainly concerned with heat recovery from the exhaust (about 500 °C) of gas turbine, which include gas to gas recuperation, steam injection, evaporation cycle, chemical recuperation and combined cycle.

Combined heat and power (CHP or cogeneration), and the combined cycle are two of the most common practices in recovering the energy from the exhaust of gas turbine. Usually steam instead of hot gas is one of the products from a CHP system. Steam can be used for many purposes such as dry, separation, and heating processes. The generated high-pressure steam from CHP can directly move the steam turbine and generate additional electrical power (most valuable form of energy), called a combined cycle. The combined cycle is known has the highest power generation efficiency in the commercial available GENSETs. To obtain a high efficiency, however a judicious selection and combination of gas turbine and steam turbine is very important. Usually the efficiency of steam turbine is very sensitive to its capacity. As the size scaled down, the frictional loss per unit flow rate rapidly increase, the overall efficiency will fall down. Therefore, the combination of a combined cycle usually consists two or three gas turbines (collecting more waste energy) matching with a steam turbine. The complexity and inflexibility of combined cycle will also make this excellent technology unsuitable to our interesting project.

To obtain both power and heat from a CHP system has been very popular, Pilavachi [4] recently gave an overview of power generation with gas turbine and CHP systems, where he pointed out some development trend in the European Union.

Beside the various mentioned processes, the steam generated from a CHP system can be also used to improve the power generation efficiency and the power generation capacity. For example, the steam can be supplied to an absorption chiller and generate a cooling capacity, which in turn can be used to cool down the inlet air of a GENSET. Najjar [5], Mohanty and Paloso [6] described in detail about the performance enhancement of gas turbines by inlet air cooling.

The steam can be directly injected into the combustion chamber of a GENSET, called steam-injected gas turbine (STIG). The added vapor mass can very effectively boost generation capacity and efficiency as it flowing through turbine. In fact, STIG has become a well-established practice [7–10]. Tuzson [11] reported the development of STIG technology including a list of available turbines for conversion.

Although many efforts have been devoted to energy and exergy analysis of gas turbine cogeneration system, however, very few studies have been conducted on the evaluation of retrofitting project for a simple cycle GENSET. In this study, we try to improve the performance for a simple cycle GENSET with GE Frame 6B as its prime mover by mainly using the recovered energy from exhaust gases such as inlet air cooling and STIG methods and other well-proven technologies. Results in this study should provide useful information to simple cycle GENSET owners and other utilities facing the increasing of energy efficiency and the reducing of emission.

2. System description and computer simulation

A simple cycle GENSET is owned by a food company in Tainan, Taiwan. The performance record indicated there is a substantial drop in power output during the summer season when the electricity from grid is the most expensive. The prime mover of this GENSET is GE Frame 6B, and its catalog data are listed in Table 1.

In order to predict the effect of system modification for this unit, a computer program is developed to simulate the base case of this system. A set of steady-state governing equations including mass, energy, entropy and exergy balances can be constructed from control volume

Table 1
Performance specifications of existing Frame 6B system under ISO condition

TIT	1380 K (2020 °F)
Compression pressure ratio	11.8:1
Net power output	38.34 MW
Heat rate	11,457 kJ/kW h
Exhaust flow rate	139.38 kg/s
Exhaust temperature	812 K
Nominal shaft speed	5100 rpm

analysis sequentially for compressor, combustor, and turbine [12,13]. The detailed descriptions of computer programming can be referred to our previous study [14].

In the analysis, the kinetic and potential energy are ignored, the adiabatic assumption is used for compressor and turbine, but a heat loss about 2% of LHV is used of combustor. The natural gas with LHV of 802,361 kJ/kmol is used as input fuel of combustor, in which a complete combustion process is assumed.

By keeping a fixed TIT(=1380 K), a fixed exhausted temperature T_4 at 812 K and a fixed compression ratio ($r = 11.8$), the calculated power output and power generation efficiency are 38.2 MW and 31.35% which are very close to the rated values of 38.34 MW and 31.4% (heat rate 11475 kJ/kW h).

During the sensitivity study, an estimated generator efficiency at 0.985 was assumed. Different combinations of compressor efficiencies and turbine efficiencies were used to calculate the overall system efficiencies and system outputs. Table 2 lists sample results, from which the pair of $\eta_c = 0.85$ and $\eta_t = 0.86$ can result the output and efficiency relatively closer to the rated values, and were thus used for analysis.

2.1. Modification cycle

As we mentioned before, the system efficiency can be improved by either reducing the compressing work or increasing the expansion work. Adding an intercooler can reduce the compressing work, and using reheat chamber can increase the expansion work. Both techniques, however require to alter the integrity of rotating machines and are thus not suitable for a retrofitting project.

Table 2
Calculated output capacities and system efficiencies at different η_c and η_t values

		$\eta_t = 0.85$	$\eta_t = 0.86$	$\eta_t = 0.87$
$\eta_c = 0.85$	W (MW)	37.23	38.20	39.17
	η_g (%)	30.29	31.35	31.95
$\eta_c = 0.86$	W (MW)	37.77	38.74	39.70
	η_g (%)	30.61	31.51	32.22
$\eta_c = 0.87$	W (MW)	38.30	39.26	40.22
	η_g (%)	30.90	31.70	32.52

For the same reason, the humid air turbine (HAT) cycle [15,16] can obtain better performance under a high compression ratio usually requires a multistage compression, intercooling, and aftercooling, and is also excluded from this analysis.

The modification cases in this retrofitting analysis include inlet air cooling, regeneration, and the STIG cycle, all of them are technology proven and commercial available.

2.1.1. Inlet air cooling

The modification of inlet air cooling is simply to either use vapor-compression refrigeration system or absorption chiller to cool down the compressor's inlet air from the average local summer ambient conditions ($P_0 = 101.3$ kPa, $T_0 = 303$ K, RH $= 80\%$) to ISO conditions.

2.1.2. Regeneration

The modification of regeneration is to install a regenerator after the compressor (see Fig. 1). By adding a regenerator at this location, the compressed air from compressor will absorb some energy from the exhaust gases before entering the combustor.

2.1.3. The STIG cycle

The injection of steam into combustor is a normal practice to boost power and efficiency [7]. A heat recovery steam generator (HRSG) is used to capture the energy from the turbine-exhausted gases and heat the purified liquid water into the injection steam and process steam (see Fig. 1). The injected steam, which can amount to 10–20% of the air mass flow rate, acts as the additional mass flow can expanding simultaneously with original air flow through turbine to boost the turbine net work. It should be noted that the required pressure of injected steam is obtained from a pump, its pumping work is much smaller (two orders in magnitude) than that of compressor. Since the specific heat of steam is almost double of air, the enthalpy and exergy (can be considered

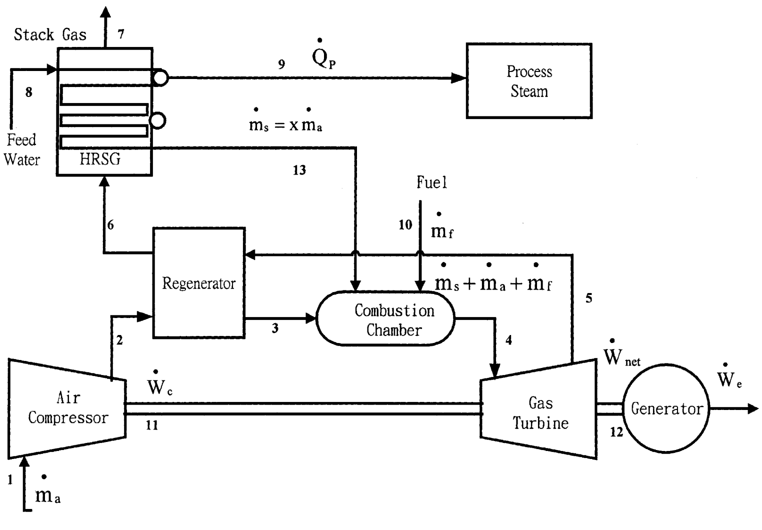

Fig. 1. Schematic diagram of retrofitted system.

as work potential) of steam is higher than that of air per unit flow rate. In addition, with a better cooling ability, the injection of steam into the combustor can greatly reduce NO_x emissions.

3. Results and discussion

The average of local summer weather conditions at $P_0 = 101.3$ kPa, $T_0 = 303$ K, RH = 80% were used to see the effect of each modification, and the obtained results are listed in Table 3.

The effect of inlet air cooling is essentially equal to the loss due to hot weather, increasing capacity from 33.86 to 38.2 MW and efficiency from 30.45% to 31.35%. In order to cool down the hot humid air at 130.86 kg/s, the estimated refrigeration capacity is around 3900 tons, which needs to consume about 3 MW electricity if a vapor-compression centrifugal chiller is used. This 3 MW will be considered as an internal (on site) load, and the net capacity will become to be 35.2 MW. However the refrigeration capacity can be also obtained from the absorption chiller, which requires about 12 MW process heat (use double-effect absorption chiller with COP = 1.2). The installation of a HRSG can recover more than enough process steam to move the absorption chiller.

Gas to gas regenerator does offer reasonable efficiency improvement (from 30.45% to 34.66%) while keeping the same output capacity (at 33.86 MW). The modification of adding a regenerator is relatively easy (without mechanical complexity) at relatively low capital cost.

STIG has the most profound improvement on both capacity (about 42% increase) and efficiency (from 30.45% up to 38.09%), but should require a relatively high capital cost. In addition to the installation of a HRSG, a specially designed steam-injection system and the associated dynamic control system [8] is also needed. The existing generator, switching gear, and transformer are rated at 50 MW plus, and thus still applicable after modification is made.

The estimated consumption of purified water for injected steam is about 60 tons/h, which is also available at the existing factory's water treatment system at $0.65 per ton. The water cost is only about 1.3% of fuel cost, but one additional water storage tank at 500 tons is needed after retrofitting.

As the compression ratio increased, both the compression work (input) and turbine work (output) increase, the net power output rises upward and then declines downward. Fig. 2 shows the maximum net power output is around $r = 11.8$ (the design value) for simple cycle. For the STIG cycle, the maximum net work occurs at a higher compression ratio.

According to manufacture's data, the compression ratio can be safely raised to $r = 13$ (still has safety margin to avoid surge) by increasing the rotation speed of compressor. From GE published data, the trends of a typical turbine map shows that a 5% change in the mass flow rate would have a negligible impact on turbine efficiency. The increase in compression ratio may change the

Table 3
Performance data for different modifications ($r = 11.8$, $T_0 = 303$ K, TIT = 1380 K)

	Simple cycle	Inlet air cooling	Regenerator	Steam injection
Power output (MW)	33.86	38.20	33.86	48.20
Generation efficiency (%)	30.45	31.35	34.66	38.09

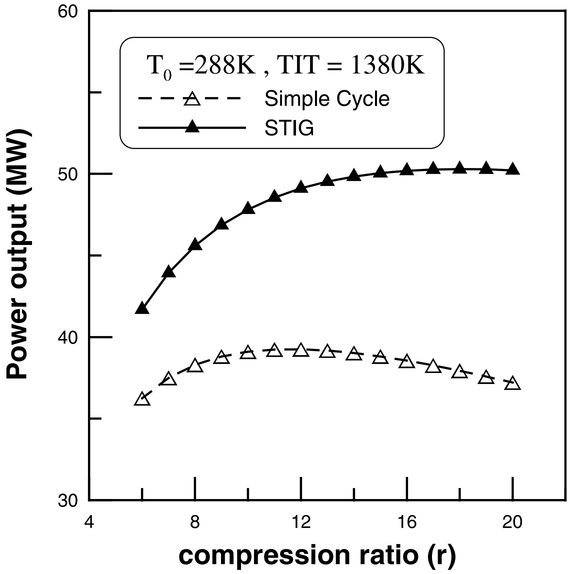

Fig. 2. Comparison of power output at different compression ratio.

compressor efficiency. However, the constant-efficiency lines on the performance map are too large to tell a clear difference when the compression ratio increasing from 11.8 to 13. The results from Table 2 also indicate a 2% drop in compressor efficiency does not significantly penalize on either output MW or efficiency. The same values of $\eta_c = 0.85$ and $\eta_t = 0.86$ obtained from the analysis of basic system are also applied in the new case.

Using the new compression ratio and other parameters listed in Table 4 to simulate the retrofitted system. The calculated results at every key position of the system are presented in Table 5,

Table 4
Conditions and parameters used in the calculation

TIT	1380 K (2020 °F)
Compressor inlet temperature	303 K
Pinch point temperature difference of HRSG	30 K
Compressor efficiency	0.85
Turbine efficiency	0.86
Generator efficiency	0.985
Compression pressure ratio	13:1
Mass flow rate of air	130.86 kg/s
Mass flow rate of process steam	6.39 kg/s
LHV of fuel	802,361 kJ/kmol
Chemical exergy of fuel	824,348 kJ/kmol
Pressure of injected-steam	1.63 MPa
Pressure of injected-fuel	1.70 MPa
Pressure loss of combustor/HRSG	5%
Pressure loss of regenerator	3%
Pressure loss of compressor/turbine	1%

Table 5
Thermodynamic properties and exergy flow rate at the key positions of the retrofitted system

State point	Pressure P (MPa)	Temperature T (K)	Mass flow rate m (kg/s)	exergy flow rate (MW)		
				Physical	Chemical	Total
1	0.10	303.2	130.86	0.00	0.00	0.00
2	1.32	664.2	130.86	47.03	0.00	47.03
3	1.28	780.0	130.86	56.31	0.00	56.31
4	1.21	1380.0	146.57	154.19	0.57	154.76
5	0.11	860.7	146.57	47.92	0.57	48.49
6	0.11	770.4	146.57	36.81	0.57	37.38
7	0.10	475.7	146.57	8.94	0.57	9.51
8	1.22	303.2	19.47	0.006	0.016	0.022
9	1.22	461.8	6.39	5.22	0.016	5.236
10	1.70	303.2	2.63	1.16	135.02	136.18
11	–	–	–	–	–	50.64
12	–	–	–	–	–	50.55
13	1.63	526.7	13.08	12.01	0.03	12.04

from which we can see $\dot{W}_{\mathrm{net}} = 50.55$ MW, the exergy at position 12. From Fig. 3, we can see the big differences in both capacity and power generation efficiency between the simple cycle and the retrofitted system. The figure also reveals the $\dot{W}_{\mathrm{net}}$ decline significantly for simple cycle but only slightly for STIG cycle under hot ambient temperature.

The exergy destruction rate ($\dot{E}_{\mathrm{D}}$) represents the waste of available energy. Exergy destructions of all components have been calculated to enhance the understanding of cycle performance. Fig. 4 presents the $\dot{E}_{\mathrm{D}}$ of each component after retrofitting. In examining the $\dot{E}_{\mathrm{D}}$ for all components, the combustor has the largest $\dot{E}_{\mathrm{D}}$ and shows the major site of thermodynamic inefficiency because of

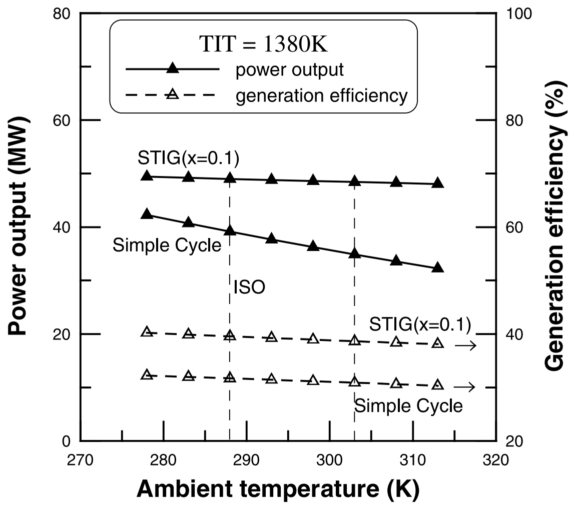

Fig. 3. The effect of ambient temperature on power output and generation efficiency.

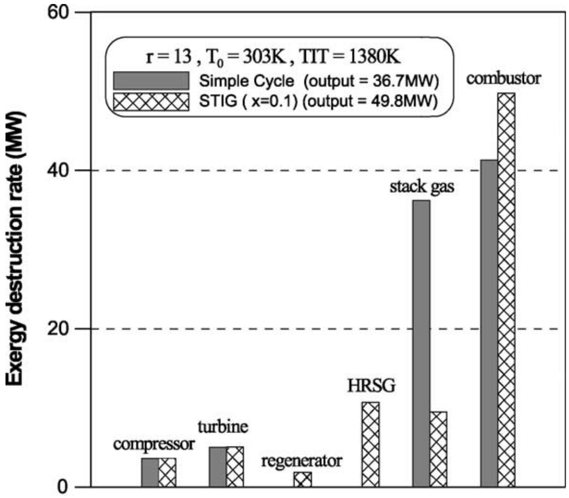

Fig. 4. Comparison of exergy destructions after retrofitting.

large irreversibilities arising from chemical reaction and heat transfer. Steam injection will increase the $\dot{E}_{\mathrm{D}}$ due to more mixing and combustion in combustor. The exergy rate at position 7 (see Fig. 1), is considered as exergy loss through stack. Because part of the exhaust heat is recovered in HRSG, the exhaust exergy out of stack can be reduced substantially after retrofitting. The exergy losses through stack will not only waste the available energy but also dump the thermal pollution to our living environment. Although the $\dot{E}_{\mathrm{D}}$ of combustor increase after the retrofitting (see Fig. 4), the exergy loss per MW output is smaller than that of a simple cycle, as shown in Fig. 5.

Exergy efficiency (ε) for each component can be defined as the ratio of $\dot{E}_{\mathrm{R}}$ to $\dot{E}_{\mathrm{S}}$, where $\dot{E}_{\mathrm{S}}$ is the exergy rate supplied to the component, and $\dot{E}_{\mathrm{R}}$ is the exergy rate recovered from the component.

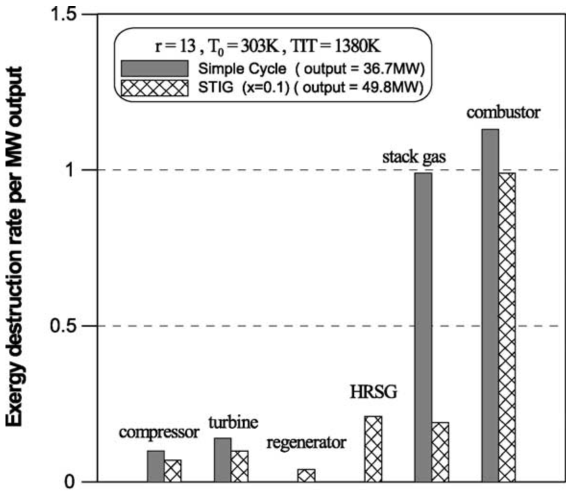

Fig. 5. Exergy destruction per MW output after retrofitting.

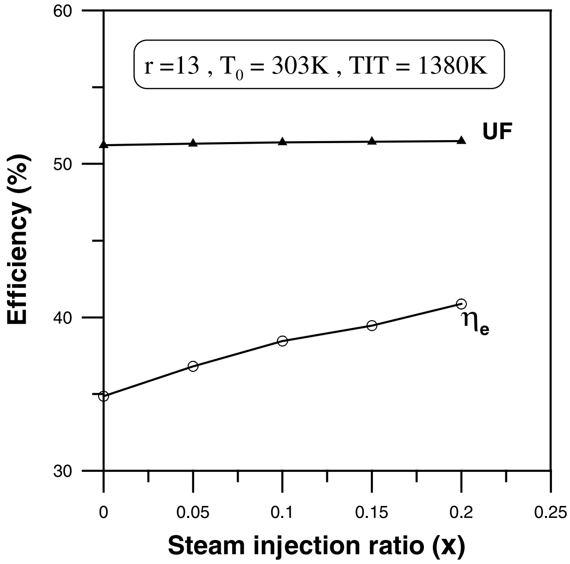

Fig. 6. The UF and generation efficiency of cogeneration system at different injection ratio.

Exergy efficiencies of compressor, turbine, combustor, regenerator, and HRSG are respectively 0.93, 0.92, 0.76, 0.83, and 0.62, among which compressor and turbine have a higher exergy efficiency. This implies most of the exergy destruction in compressor and combustor are inevitable. It is interesting to see although the exergy destruction rate of combustor is the highest (see Fig. 5), the exergy efficiency of combustor is higher than that of HRSG. Therefore, there should exist a greater improvement margin for HRSG than for combustor.

For a cogeneration system, the overall (heat and power) efficiency is usually called the utilization factor (UF), which is defined as $(\dot{W}_{\mathrm{net}} + \dot{Q}_{\mathrm{p}})/\dot{m}_{\mathrm{f}}$ (LHV), where $\dot{Q}_{\mathrm{p}}$ is the heat rate of process steam, see the position 9 of Fig. 1.

Fig. 6 shows the efficiency of power generation increased and UF kept steady as the injection ratio increased. It is obvious the quantity of process steam become less as the injection steam is increased. Since UF does not change much as injection ratio increased, the increasing rate of $\dot{W}_{\mathrm{net}}$ (electric power, which is about five times valuable than steam) is about equals to the decreasing rate of $\dot{Q}_{\mathrm{p}}$ (steam). This result also indicates that the heat-to-power ratio of a STIG cogeneration system is relatively flexible.

4. Conclusions

Like many countries, energy efficiency and environment impact are the most important issues in the development of our power generation policy. Recover the energy from the exhaust gas of a simple cycle GENSET can be used back to the system to improve the system's generation capacity as well as efficiency. In this study, we showed the modifications of STIG and regeneration to GE Frame 6B simple cycle can boost the efficiency improved from about 30% to 40%, the capacity from 38 to 50 MW. The NO_x emission can also be reduced substantially by the injection of steam into combustor. Although the steam injection will increase the total exergy losses, the exergy loss per MW output is much smaller than that of simple cycle. It also reveals that the degree of energy wasting and thermal pollution can be reduced after retrofitting.

Acknowledgements

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