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Parametric Simulation on Enhancement of the Regenerative Gas Turbine Performance by Effect of Inlet Air Cooling System and Steam Injection

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ABSTRACT

Iraq being one of the developing countries of the world considers energy efficiency and the impact of its generation on the environment an imperative process in improvement of its power generation policies. Iraq bearing high temperatures all year long results in reduction of air density, therefore, Inlet air Cooling and Steam Injection Gas Turbines are a striking addition to the regenerative gas turbines. Regenerating Gas turbines tend to have a high back work ratio and a high exhaust temperature, thus, it leads to a low efficiency in power generation in hotter climate. Moreover, STIG and IAC through fog cooling have known to be the best retrofitting methods available in the industry which improve the efficiency of generation from 30.5 to 43% and increase the power output from 22MW to 33.5MW as the outcomes of computer simulations reveal. Additionally, this happens without bringing about much extensive change to original features of the power generation cycle. Furthermore, STIG and spray coolers have also resulted in power boosting and exceeding generation efficiency of gas turbine power plant.

Keywords: heat pipe, constant conductance heat pipe, effect of working fluid quantity of heat pipe performance.

Introduction

Industrial Power Plant also known as Gas turbines power plants are used extensively in every form of industry for the purpose of generation of electricity as well as power the turbines, compressors or power pumps needed to run those industries[1]. Moreover, Gas turbines are also referred to as naval gas turbines when used in aircrafts. Gas turbines are the most common form of power generation resource available to many industries, but they are usually made to work for long time periods, under conditions that do not necessarily agree to their design specifications [2]. Thus, understanding the true working of Gas turbines is one of the most important factors on the economy of a developing country [3]. As power generation is directly proportional to the working of industry, hence for appropriate optimization of any industry, the proper working of a gas turbine needs to study [4]. It is the main source of power production in any industry [5]. A gas turbine consists of three distinctive components which are compression, chamber and turbine. The individual and specific evaluation of these components consists of thermodynamic processes like compression, expansion and combustion. Furthermore, the thermodynamic analysis of any gas turbine includes measurements of performance parameters like thermal efficiency, power output and particular fuel consumption and can be executed with the help of Brayton cycle [6].
Gas turbines results in huge amount of exhaustion of gases, thus leading to loss of huge amounts of energy into the environment (which are exposed to the atmosphere 400ºC to 500ºC). Although, a great amount of heat energy is recovered from exhaust gases, some of it is used into regeneration of power through their gas turbines. Turbine work is extensively

used to compress the inlet-air in the compressor of the gas turbine to further boost its own performance [7, 9]. Moreover, many retrofitting methods are used such as Li-Br-water refrigeration system and spray cooling system (evaporating cooling), which cool the inlet compressor air to further reduce the work of the turbine and increase its efficiency. Furthermore, STIG is also an effective method used to recover energy of the exhaust gases.

STIG and inlet air spray cooling system are engaged with regenerating gas turbine cycle to increase its efficiency. Enhancement of power generation is a result of these two retrofitting methods. This further helps in developing the economy as well, as economy is directly proportional to the working of industries [8, 10]. Therefore, proper implementation of these techniques need to done and we need to understand the proper working of the two ways. Spray cooling systems sprays water at normal condition into air by the help of which the transfer of heat within air and water takes place. Furthermore, the increase of water usage and demineralization of water reduces the environmental friendly nature of the turbines towards the society. Subsequently, these two systems result in a great increase of power generation and boost to its power output.

System Description

Figure 1 shows a regenerative cycle two-shaft gas turbine system. It primarily consists of compressor, combustor, gas turbine and a generator. The system shown in the figure is incorporated with both injection gas turbine and inlet air cooling. It is also installed with an evaporative fog cooling system (FCS) to reduce the temperature of ambient air to state point 0. A standard fog cooling system includes an array of manifolds present at some distance across the compressor inlet duct; these manifolds are fed by a high pressure pump skid. In order to create cooling effect, fog cooling being an active system uses special atomizing nozzles that eject extremely small droplets of water under high pressure; these nozzles are found at distinct spots across the inlet duct at high pressure. There are a specific number of nozzles in these manifolds which release high pressure water into the inlet air. Factors such as dry and wet bulb ambient conditions are vital for monitoring the amount of fog introduced to get the required amount of cooling. Each nozzle produces approximately 2.8 billion droplets per second and its discharge is 2.8ml/s. These mini droplets are in fact fog itself which, because of their fineness evaporate rapidly and drop the inlet air temperature. Other than its basic components, a gas turbine such as this also installed with a heat recovery steam generator (HRSG) located at the downstream exit of the turbine (state point 7); the purpose it to salvage the heat from the exhaust gases. The superheated steam yielded by HRSG is divided in two parts, where only a fraction of it is used for STIG (state point 10) and the rest is taken up for various processes.

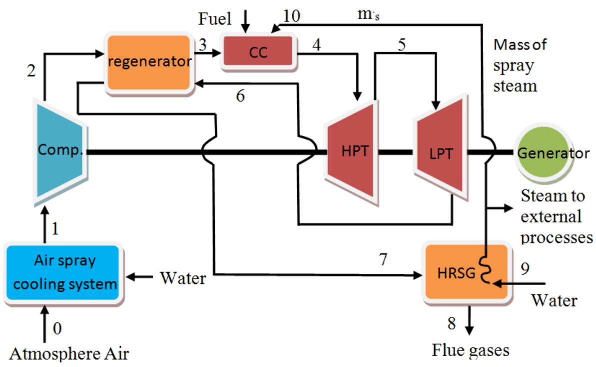

Fig.1: Regenerated gas turbine cycle with fog cooling and STIG

Thermodynamic Model and Analysis

Alterations in the inlet air cooling system and steam injection of the gas turbine have been thoroughly studied under the light of thermodynamics; comprehensive energy analysis has been carried out to examine the Baiji mobile gas turbine plant. The energy calculations of the gas turbine, steam injection system and inlet air cooling system are carried out. The following points [1-3] sum up the assumptions made for the study of the gas turbine and cooling system:

1. The temperature difference between flue gas and superheated steam, also known as Terminal Temperature Difference (TTD) is assumed to be 20°C in the HRSG.
2. Any decrease in pressure in the combustion chamber and HRSG is ignored.

3. Any heat losses incurring in the combustion chamber, turbines and HRSG are also ignored.
4. Following atmospheric conditions are assumed:
   - Temperature, 288K
   - Pressure 1.01325 bar
   - Relative humidity 60%
5. The maximum temperature of steam cycle is taken to be 833K.
6. Compressor and gas turbines have 85% isentropic efficiencies.
7. 3% of the fuel lower heating value is taken to be the heat loss in the combustion chamber [11]. All other components are supposed to be adiabatic.
8. Tap, approach point is taken to be 5°C in HRSG.
9. The minimum temperature difference between the flue gas and the saturated steam, also known as pinch points (Tpp), are taken as 15°C in HRSG [12].
10. Pressure in the condenser is supposed to be 0.12 bar.
11. All process are assumed to be steady-state and steady flow.
12. Fog cooling system has been maintained for 100% saturation of ambient air at wet bulb temperature of air.
13. Constant temperature has been maintained in combustion chamber.
14. It is assumed that the fuel injected into the combustion chamber is natural gas.
15. It is supposed that the nozzle discharges water into the evaporative cooling chamber at a pressure of 140 bar when it transforms into fog (tiny droplets). It absorbs latent heat of air through adiabatic mixing.

Using a set of steady-state equations which include mass, energy balances using control volume analysis serially for compressor, combustor, gas turbine and HRSG, MATLAB has made a code to compute and simulate the retrofitting methods over simple gas turbine power plant.

A set of equations which influence a particular component ‘n’ may be called Mass Rate Balance:

$$\sum_{in} \dot{m}_{in,n} = \sum_{out} \dot{m}_{out,n} \quad (1)$$

Therefore, Energy rate Balance is:

$$\dot{Q}_{cv,n} - \dot{W}_{cv,n} = \sum_{out} \dot{m}_{out,n} h_{out,n} + \sum_{in} \dot{m}_{in,n} h_{in,n} \quad (2)$$

Regenerator is a significant kind of heat exchanger, the function of which is to heighten the energy of the hot stream from the compressor before it enters the combustion chamber. Preheating enhances combustion [13].

$$\varepsilon = \frac{T_3 - T_2}{T_6 - T_2} \quad (3)$$

In the heat recovery boiler, heat transfer between the condensed water and exhaust gases takes place and super-heated steam is produced.

$$m_{exh}\left(h_7 - h_8\right) = m_w\left(h_{steam} - h_{water}\right) \quad (4)$$

Where:

- mexh= mass flow rate of exhaust gases of turbine
- mw= mass flow rate of condensate water
- h_7, h_8, hsteam and h_w= enthalpies of exhaust gases at state 6 and 7, super-heated steam and condensate water respectively.

The equation representing heat transfer that occurs in an evaporative cooling system or a fog cooling system is:

$$m_{evw}\left(h_{v1} - h_{w0}\right) = m_{air}\left(h_{air0} - h_{air1}\right) + m_{steam} m_{air}\left(h_{v0} - h_{v1}\right) \quad (5)$$

Where:

- m_{evw} = mass flow rate of cooling water
- h_{w0} = enthalpy of cooling water
- ma= mass flow rate of dry air
- $\left(h_{v0} - h_{v1}\right)$= enthalpy change of water vapour during cooling
- $\left(h_{air0} - h_{air1}\right)$ = enthalpy change of dry air

The following equation represents the thermal energy (ηth) of a thermal system:

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_f} \quad (6)$$

It is the ratio of network output to net heat input of the fuel.

Where:

- $\dot{W}_{net}$ = net work output
- $\dot{Q}_f$ = total heat input of the fuel

Generation efficiency (η_{gen}) of a thermal system is represented as:

$$\eta_{gen} = \frac{\dot{W}_{elc}}{\dot{Q}_f} \quad (7)$$

It is defined as the ratio of electrical power output (W_{elc}) to the total heat input of the fuel (Q_f).

$$HR = \frac{\dot{Q}_f}{\dot{W}_{elc}} \quad (8)$$

(HR) Heat Rate is the ratio of heat produced by the fuel $\dot{Q}_f$ to the electrical power output $\dot{W}_{elc}$ of the thermal system. Based on cost effectiveness, another factor considered to measure the thermodynamic performance of a cogeneration system is the ratio of power to heat [14]:

$$P_{RH} = \frac{\dot{W}_{elc}}{\left(\dot{Q}_{eva} + \dot{Q}_{prod}\right)} \quad (9)$$

Cost is directly related to the amount of power such a system can produce in return of the amount of process heat added.

The ratio of mass of fuel to the network output is called Specific Fuel Consumption (SFC) [13, 14]:

$$SFC = \frac{\dot{m}_f}{\dot{W}_{net}} \quad (10)$$

It is reciprocal of specific network (W_{spec}).

According to the first law of thermodynamics, thermal efficiency (η_I) is the ratio of all the useful energy absorbed from the system (electricity and process heat) to the energy of fuel input.

$$\eta_I = \frac{\dot{W}_{elc} + \dot{Q}_{pro}}{\left(\dot{Q}_f\right)} \quad (11)$$

Where:

- (Q_{pro})= process heat rate

First-law thermal efficiency may also be called Fuel Utilization Efficiency or Utilization Factor or Energetic Efficiency.

The ratio of useful energy (network output and process heat) to the heat supplied by the fuel is known as the Energy Utilization Factor (EUF) [15]:

$$EUF_{COH} = \frac{\dot{W}_{net} + \dot{Q}_{pro}}{\left(\dot{Q}_f\right)} \quad (12)$$

The net energy output to the total energy output of the power generation system is called the Fuel Energy Saving Ratio (FESR) [11, 15]:

$$FESR = \frac{\dfrac{\dot{Q}_{pro}}{\eta_{HRSG}} + \dfrac{\dot{W}_{net}}{\eta_{GT}} - \dot{Q}_f}{\dfrac{\dot{Q}_{pro}}{\eta_{HRSG}} + \dfrac{\dot{W}_{net}}{\eta_{GT}}} \quad (13)$$

Results and Discussion

Following are the four configurations with retrofitting that have been investigated in relation to simple gas turbine cycle:

1- Regenerative gas turbine cycle
2- Regenerative gas turbine cycle with inlet air cooling (IAC)
3- Regenerative gas turbine cycle with STIG
4- Regenerative gas turbine cycle with both IAC and STIG.

The systems listed above were run on a computer program in MATLAB for performance analysis. While doing computations, turbine blade cooling was neglected for steady state operations.

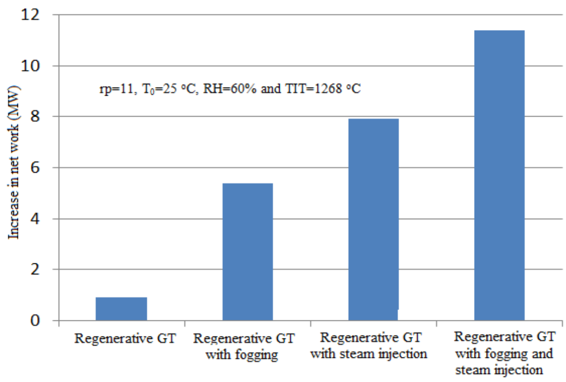

Fig. 2: Net work output for retrofitted cycles in comparison to simple GT cycle

Fig. 2 shows how the performance measures of simple gas turbine cycle contrasts with other combinations cycle. The compositions and proportions of gases and many estimated performance parameters are taken into account for calculation of temperature, pressure and gas concentration in each component. Performance parameters such as system efficiencies, heat rate and specific power output etc., are greatly improved with the incorporation of evaporative cooler in a regenerative cycle. The resulting power generation efficiency and net output for regenerative cycle are 6.99% and 21.8 MW respectively. Gas turbine inlet air fogging uses very small droplets, sizes varying from 3 to 16 microns of fog converted from de-mineralized water which is projected by special atomizing nozzles working at 140 bar to cool the intake air. Because of the miniscule size of the droplets in the intake duct the air temperature drops and subsequently improves power performance by increasing the moist air mass flow rate. Approximately 100% evaporation effectiveness can be achieved in terms of attaining saturation conditions and wet bulb temperature at the compressor inlet. Therefore, change in the ambient temperature affects the exhaust temperature of the compressor, the internal and external temperature of the turbine, the mass flow, the specific work, the specific fuel consumption and power. The power supplied by the machine is inversely proportional to ambient temperature; as the ambient temperature decreases, the power supplied increases. Hence, it is important to cool the compressor inlet air to achieve a higher supply of electric power which also reduces the work to be done by the compressor. Hence, evaporative cooling is employed as an effective way of cooling inlet air from 25ºC and 60% RH up to 18.33ºC. In dry summers, the influence of evaporative cooling will be higher in Iraq when there is greater dry bulb temperature and lesser RH. Figs.2 and 3 draw the comparison between a regenerative cycle gas turbine with fog and one without fog cooling. The net power output adds up by 6.1% and many other efficiencies increase by 0.91%, whereas the heat rate drops by 2.1%. Figs. 2 and 3 also weigh regenerative cycle gas turbine with STIG and without STIG; again, the net power output and thermal efficiency escalate by 24% and 4% respectively whereas 11.5% of drop in heat rate is observed. The temperature at the outlet of the stack, shown in Fig.1 at state point 7 is maintained above the dew point temperature of acid, i.e. 131ºC. The purpose of this control is to avoid condensation of SO_2 and NO_2 which ultimately hydrolyse into sulphuric acid (H_2SO_4) and nitric acid (HNO_3) respectively and cause damage to the air pre-heater of HRSG such as scaling and corrosion. Under these conditions, generated superheated steam at 813.15K and 22bar has a the highest flow rate of around 16.27 kg/s when the pinch point and approach point for current investigation are taken as 15ºC and 5ºC respectively. There is an impressive range of STIG available to optimize the power cycle; generated steam injected into the combustor (STIG only) yields a maximum injection ratio (m_{steam}/m_{air}) of around 0.2 which is quite considerable. The net power output can be raised to 34.15MW by pumping as its value is 2 to 3 orders lower than that of a compressor; the net power output produced by the steam is, thus quite high as compared to that of air per unit mass flow rate. The pump itself can make STIG alone to create profound impact. Other than that, the superheated steam has almost twice specific heat as compared to air and the enthalpy of steam is greater than that of air at a particular temperature. The STIG method quite successfully increases the net power output and increases the overall efficiency of the gas turbine. System efficiencies get sizably enhanced in a regenerative gas turbine cycle with STIG (for steam injection ratio 0.2). Weighing regenerative cycle gas turbine with fog cooling and STIG against one without fog cooling and STIG reveals that net power output shoots up by 11.9% and thermal efficiency, by 9.81%, the heat rate, however, decreases by 11.2%. It may therefore be concluded that incorporation of simple cycle with STIG and fog cooling greatly enhances system performance. Fig. 3 shows the comparison drawn between generation efficiencies for simple, regenerative and enhancing cycles.

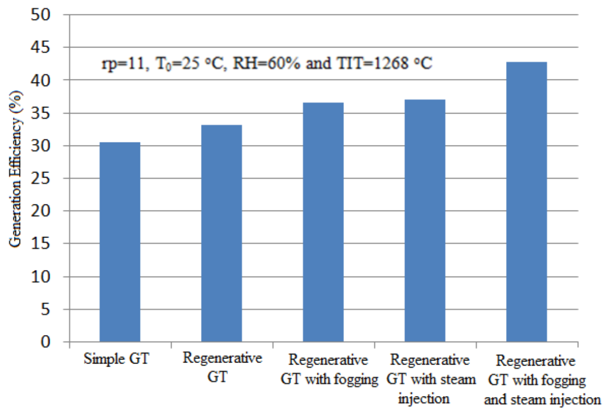

Fig. 3: Generation efficiencies for simple, regenerative and enhancing

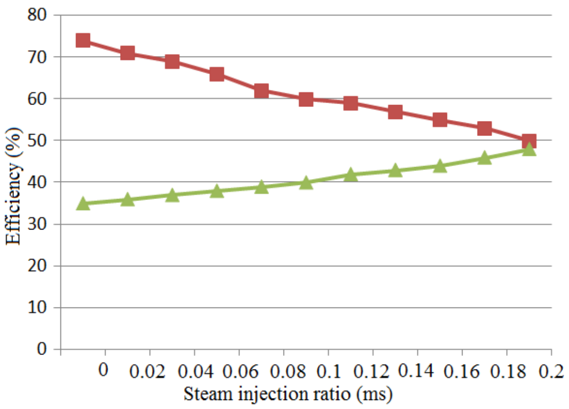

Fig. 4: Effect of steam injection ratio on first-law efficiency and generation efficiency for regenerative GT combined with fog cooling and STIG.

Fig.4 reveals how generation efficiency is influenced by STIG; it also shows its effects on first law of efficiency for fixed inlet air conditions under maximum of 100% air saturation because of the cooling caused by fog. In simple cycle gas turbine, the incorporation of fogging and STIG is seen to improve the system performance according to both first and second laws. For retrofitted combined cycle (fog cooling and STIG), the maximum generation efficiency achieved is 45.21% with injection ratio 0.2. Figure 5 shows that the rate of reduction of process heat is steeper than the slope of energy efficiency. As a result the first law efficiency decreases with increasing amount of steam injection ratio. At 0.2, the maximum injection ratio is still below the allowable injection limit as recommended by the manufacturer for the available industrial turbines because the energy extracted from HRSG restricts the maximum amount of injection steam.

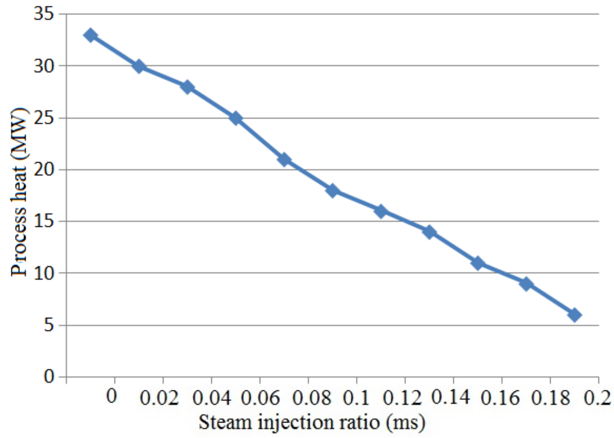

Fig.5: Effect of steam injection ratio on the process-heat for regenerative GT combined with fog cooling and STIG

Conclusions

With the rapidly increasing demand for electricity in the developed countries like Iraq, and the expected shortage in power supply due to delays in the major power projects, retrofitting regenerative gas-turbines with inlet air pre-cooling and STIG are attractive investment opportunity. Recovering the energy from the exhaust gas of a regenerative cycle can be used back to the system to improve the system performance. Steam injection and inlet air evaporative cooling are well-proven technology that can effectively improve power output and power generation efficiency for a regenerative cycle gas turbine. In the present work, a regenerative cycle gas turbine has been investigated. An existing simple cycle gas turbine was considered as the basic system and has been converted into modified retrofitted system with regenerative, inlet air cooling, and STIG. The steam needed in the STIG feature is generated from the energy recovered from the system's own exhaust gases. Under the average local weather conditions (25ºC and 60% RH), the benefit of adding the STIG feature can substantially improve the power output from the 22 MW to 33.5 MW and power generation efficiency from 30.5 to 43 %. It also reveals that the degree of energy wasting and thermal pollution can be reduced through retrofitting. Although the performance of spray coolers is deeply influenced by the ambient temperature and humidity, they operate efficiently during hot and dry climatic conditions.

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