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Effect of Steam Injection on the Performance of Heavy-Duty Gas Turbines

تأثير حقن بخار الماء على أداء التربينات الغازية ذات القدرات الكبيرة

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ملخص

لقد تم إستخدام برنامج محاكاة من الحزم الجاهزة وذلك لبناء موديل يمكن إستخدامه كأداة فعالة لمعرفة معاملات أداء التربينات الغازية ذات القدرات الكبيرة موديل SGT5-4000F بطريقة سلسة ودقيقة

عند مقارنة النتائج التى تم الحصول عليها من هذا النموزج مع البيانات التى تم تجميعها من الواقع لتربينات فعلية (لنفس ظروف التشغيل) وجد تطابقا كبيرا بينهما مع وجود تجاوز فى حدود 4%. هذا النموزج تم بناؤه ليعمل فى الحالات المستقرة والحالات الانتقالية متضمنا انظمة التحكم المختلفة للوصول الى أقصى قدرة يمكن الحصول عليها من التربينة وذلك تحت ظروف تشغيل مختلفة.

وهذة الدراسة تهدف الى إستخدام النموزج الذى تم بناؤه لدراسة تأثير حقن بخار الماء على أداء التربينات الغازية وأهمها القدرة الناتجة من التربينة وكفاءة التربينة وذلك عند العمل تحت ظروف ثابتة من درجة حرارة الجو بالإضافة الى دراسة تأثير تغير درجة حرارة دخول الهواء على معاملات أداء التربينة. وقد أظهرت النتائج وجود تحسن كبير فى أداء التربينات الغازية عند إستخدام هذة التكنولوجيا (تكنولوجيا حقن بخار الماء).

Abstract

A gas turbine performance prediction tool has been implemented using a simulation software package to accurately predict the performance of SGT5-4000F heavy-duty gas turbines.

Comparing the results obtained from this simulation with data collected from the field, a significant agreement between them is found within an acceptable tolerance of about 4%. The model has been built to work at both steady state and transient combining the control protocols, thus achieving the maximum allowable output power with various operating parameters.

This study aims to use the implemented model to investigate the effect of Steam Injection Gas Turbine cycle (STIG) as well as the change in ambient temperature on the performance of the unit in terms of both output power and efficiency. The results indicate a significant improvement in performance using this specific technology.

Keywords

Gas Turbines, Steam Injection, Aspen Hysys, STIG, Turbine Performance.

1. Introduction

Almost all industrialized countries are now facing some degree of electric power shortage. The major problem is probably the lack of suitable sites for building new power plants of whatever type or size. Other countries face the challenge of a big gap between the electrical power demands along the year, forcing them to construct new power plants that would only be working during such period. Moreover, increasing environmental awareness has resulted in more demanding requirements in terms of preliminary analysis, prolonging and complicating the plant commissioning process.

The cycle of a gas turbine is a very flexible cycle so that its parameters of performance can be improved, by adding additional components to a simple cycle [1, 2]. For this purpose, various methods (regeneration, intermediate cooling, pre-

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heating, and steam or water injection) were used in order to improve the gas turbine performance [3-18].

The STIG method stands for steam-injected gas turbine. The heat recovery steam generator (HRSG) usually has three pressure levels and reheat [19,20]. The steam from the high-pressure (HP) steam turbine could be 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. 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 given temperatures. Therefore, the STIG method is a very effective way to boost the net power output and increase the overall efficiency of gas turbines. Presently, the STIG technology is applied only to standalone gas turbine cycle and it is not extended to the combined power cycle. The reason may be due to the decreased steam turbine output with steam injection. The combined cycle is now well established and offers superior performance to any of the competing systems. The exhaust flow through the existing HRSG is also increased, thus benefiting the steam cycle [21,22]. Steam injection in the combined cycle increases the gas cycle output but the steam cycle output decreases. However, proper selection of parameters for combined cycle such that the rise in gas cycle output is more than the drop in steam turbine output; the combined cycle output can be increase with the steam injection.

In 1978, Cheng [23] proposed a gas turbine cycle in which the heat of the exhaust gas of the gas turbine is used to produce steam in a HRSG. This steam is injected in the combustion chamber of the gas turbine, resulting in an efficiency gain and a power augmentation. Rice [24] developed a steam injected gas turbine cycle with a topping in which a HP steam is first expanded in a backpressure steam turbine, producing power, and then is injected into the combustion chamber of the gas turbine. Borat [25] found that the efficiency and the net output of the gas turbine increased considerably, of the order of 20–40 percent with the steam injection. Poullikkas [26] reviewed the gas turbine technologies and emphasized on various advance cycles involving heat recovery from the gas turbine exhaust, such as, the gas to gas recuperation cycle, the combined cycle, the chemical recuperation cycle, the Cheng cycle, the humid air turbine cycle, etc. Gigliucci et al. [27] presented the main results of thermodynamic analysis of a cogenerative cycle, which deals with a hydrogen-fed, with steam injection in the gas turbine itself to couple high process efficiencies with very low nitrous oxide emissions.

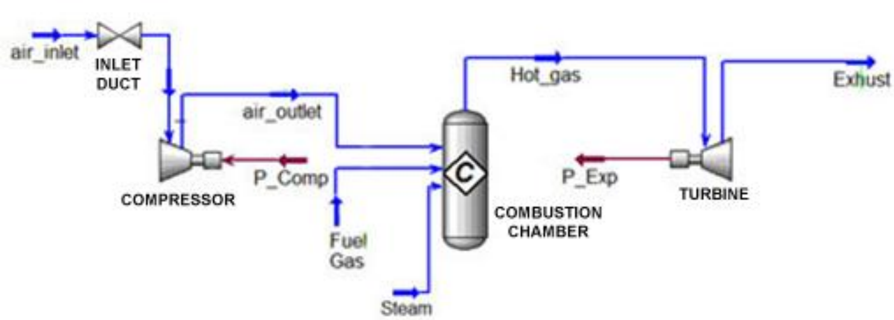

Figure 1 Model scheme built with Aspen Hysys

Steam injection also allows for a more flexible steam-production to power-production ratio [28]. Wang and Chiou [29] proved that the techniques namely steam injection gas turbine and inlet air-cooling are very effective features that can use the generated steam to improve the power generation capacity and efficiency

The principal objective of this work consists of the study and the modeling of the steam injection influences, at the upstream of the combustion chamber, on gas turbine performance.

2. Computational Investigation

Aspen HYSYS [30] has been chosen as a simulation environment for the present study as it is a powerful engineering simulation tool with a strong thermodynamic foundation. The flexibility of its design and the accuracy and robustness of its property calculations lead to the representation of a more realistic model.

All the mathematical models for each used components are built into the software where the user have to configure each object and design the process desired, and all equations used by the software available in the User Manual[30]

Not only it can use a wide variety of internal property packages, it can use tabular capabilities to override specific property calculations for more accuracy over a narrow range. It can also use the ActiveX functionality to interact with externally constructed property packages. Using Extensibility, it can extend Aspen HYSYS so that it uses property packages that created within the Aspen HYSYS environment. The built-in property packages provide accurate thermodynamic, physical, and transport property predictions for hydrocarbon, non-hydrocarbon, petrochemical, and chemical fluids.

The design point of a gas turbine is usually defined as the operating point of the engine for maximum power output with desired cycle efficiency undersea level static conditions of the international standard atmosphere (ISA). The GT engine performance is the function of its cycle parameters. In the conceptual design phase, a model that works over a wide range of operating conditions and over large parametric variations in engine design is generally aimed for, then True and validated critical inputs such as component maps and control schedules are established.

Generalizing engine models use alternate methods that work with available data of component maps and employ simplified assumptions such as constant component efficiency, fixed pressure losses, and a fixed geometry of blades etc. at all working points to compute the GT engine steady-state performance.

These types of engine models are not expected to reproduce the performance of any specific engine cycle. The primary purpose is to quickly estimate the engine performance during parametric studies, with reasonable levels of accuracy Thus, an initial baseline design model to identify the regions of the optimum solution is a good starting point to simulate the performance of GT engines.

The employed assumptions for the model in question are:

- Combustion process is represented as a 100% conversion reaction
- The compressor and turbines efficiencies are adiabatic
- Natural gas is assumed to be mainly methane 98%
- The natural gas in the feed comes directly at the pressure of the combustion chamber
- Neglecting mechanical losses

For an accurate and realistic gas turbine design point model, it is necessary to choose a set of constants that imply the characteristics of the individual components.

The constants can be divided into three groups as:

- Boundary conditions, which have to be attained and cannot be exceeded
- Thermodynamics and fluid dynamics parameters like mean specific heats at constant pressure and at a constant volume, and gas constant etc.
- Technological constants which represent current levels of manufacturability for the engine

The fixing of two main thermodynamic variables, turbine entry temperature and compressor pressure ratio defines the design cycle completely for a fixed geometry engine [31]. However to avoid any significant changes in the simulation at a later stage it is vital to list all the possible constants, which may affect the design point simulation. The program should not only be able to provide the user with entries for operational envelop data, but also engine components design conditions.

Table (1) shows the cycle design point data of the Gas turbine performance simulation (GTPS) under the influence of the International Standard Organization (ISO) ambient conditions of 15ºC and 60% relative humidity. It is based on values chosen from engine specifications of the Siemens SGT5-4000F [32], yet some data selected based on open literature and intelligent guess.

Table 1 Specifications of Siemens SGT5-4000F

Item	Specifications
Speed, *rpm*	**3000**
Gross power output, *MW*	**272.8**
Gross efficiency, *%*	**39.8**
Exhaust temperature, *ºC*	**577**
Exhaust mass flow, *kg/s*	**668**

The Optimizer performs steady state optimization by finding values of process variables that minimize or maximize a user defined objective function.

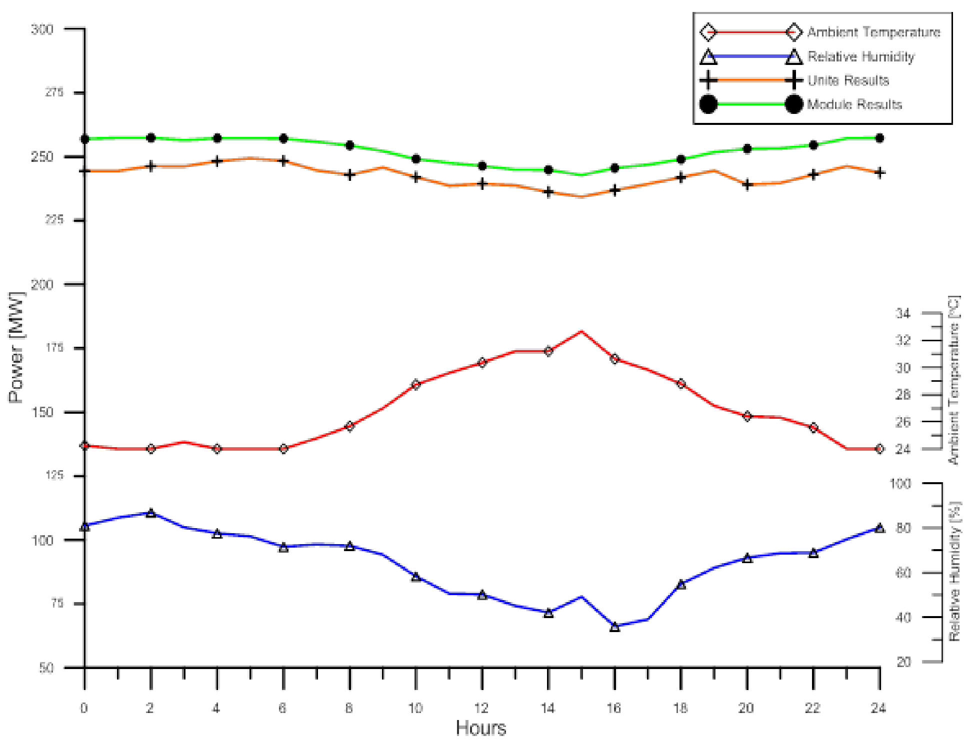

Figure 2 Comparison between the performance of the constructed model and actual operating unit along one day

It has its own spreadsheet with attached variables that define the objective function and mathematical expression relating to each variable. Constraints are the restrictions or limitations that placed on requirements or design of the process. The constraints of the process are tabulated in the Table (2).

Table 2 List of constrains

Ambient Temperature, *ºC*	**15**
Ambient Relative Humidity, *%*	**60**
Fuel Temperature, *ºC*	**20 – 30**
Combustion Temperature, *ºC*	**< 1500**
Exhaust Temperature, *ºC*	**577**
Speed, *rpm*	**3000**
Exhaust Mass Flow Rate, *kg/s*	**< 668**

The model created with Aspen Hysys is presented in Figure (1) where all objects and streams are specified based on the previously discussed parameters while the mathematical equations used are part of the software package.

The generated model has then been put into a validation process by comparing its performance to the one of an existing Heavy-Duty Gas Turbine located in Talhka Power Plant; along a whole day while the ambient conditions changes.

3. Results and Discussion

Running the optimizer with applying constrains for obtaining maximum output power and efficiency, gives results which are presented in Table (3).

The validation process revealed a significant agreement between them with maximum deviation of 4% as shown in Figure (2).

Steam injection is a mean of boosting the gas turbine output power by the means of injecting steam into the combustion chamber, thus increasing the mass flow rate entering the turbine and cooling the combustion chamber, thus allowing the controller to burn more fuel to maintain the turbine inlet temperature (TIT) constant, the total increase in mass flow result in a power increase.

The steam to be injected to the gas turbine has a pressure slightly above the combustion chamber pressure by about 4 bars, with temperature of 250 ºC.

Table 3 Optimization results

Turbine Power, *MW*	**545.65**
Compressor Power, *MW*	**296.1**
Net Power, *MW*	**272.28**
Efficiency, *%*	**41**
Air mass flow rate, *kg/s*	**676.9**
Fuel mass flow rate, *kg/s*	**15**
Air to fuel ratio, -	**44.9**
Turbine Inlet Temperature, *ºC*	**1230**

Efficiency increase however is a result of the increase in pressure ratio due to injecting the steam in the combustion chamber as the more steam to inject the more the pressure ratio will become.

Figure (3) shows the effect of Steam injection with steam-to-air ratio on the gas turbine performance. From this figure, it can be seen that the turbine output power as well as the cycle efficiency are increased by increasing the steam-to-air ratio. The turbine output power is increased due to increasing the mass flow rate where the efficiency is increased as a result of pressure ratio increasing.

Figure (4) and Figure (5) show the effect of steam injection on the performance of a gas turbine with change in steam-to-air ratio, both output power and efficiency compared to ISO conditions, where higher ambient temperature lowers the air density thus reducing the amount of air entering the compressor, causing power decay then the controller acts to maintain constant exhaust temperature by reducing fuel flow thus reducing pressure ratio causing a drop in efficiency.

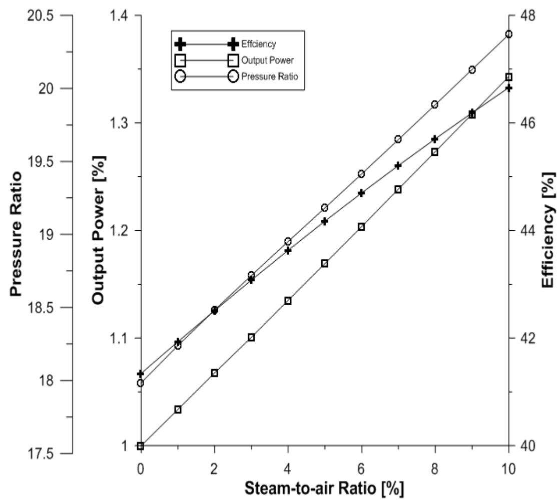

Figure 3 Effect of Steam injection ratio on Gas turbine Performance

4. Conclusion

A Heavy-duty gas turbine model has been carried out to inspect the effect of steam injection on cycle performance.

By applying 10% steam-to-air ratio, the gas turbine output power and efficacy, reaching 134% and 112% of the base load values respectively.

The study has limited the Steam-to-air ratio to 10 % because the increase in the Steam-to-air ratio causes an increase of the engine pressure ratio which endangers the compressor by pushing the operating point into surge region, this present a limitation to the use of the STIG cycle. The injection of steam created from properly treated water does not affect the life of the hot section of the turbines. This is based on a large number of units where steam injection has been used.

There is no effect of change in ambient temperature on the steam injection performance itself, yet it has the effect on the compressor that would be noticed even without any steam injection performed.

Abbreviations	
GT	**Gas Turbine**
GTPS	**Gas Turbine Performance Simulation**
HP	**High Pressure**
HRSG	**Heat Recovery Steam Generator**
ISA	**International Standard Atmosphere**
ISO	**International Organization for Standardization**
STIG	**Steam Injected Gas Turbine**
TIT	**Turbine Inlet Temperature**

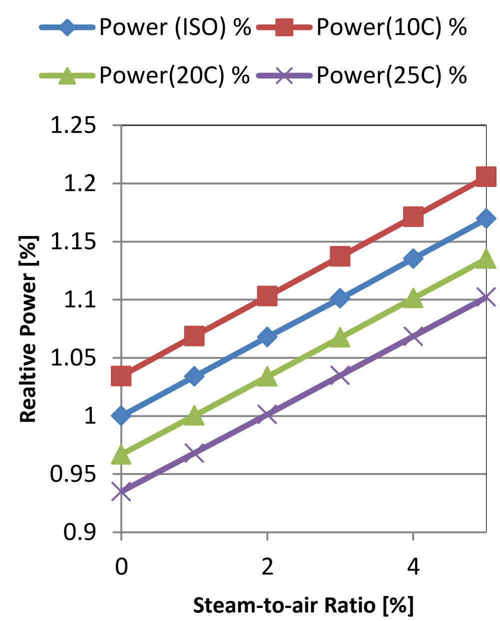

Figure 4 Effect of steam-to-air ratio on the power at different inlet air temperatures

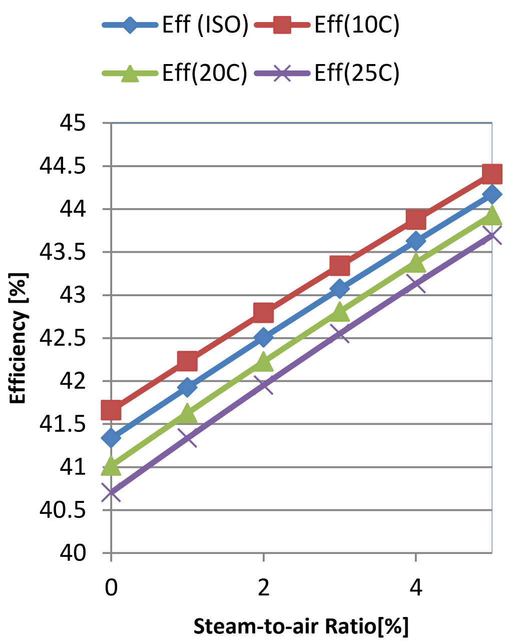

Figure 5 Effect of steam-to-air ratio on the efficiency at different inlet air temperatures

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