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Thermodynamic Analysis on Steam Injected Gas Turbine cycle

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ABSTRACT

This paper presents thermodynamic methodology for the performance evaluation of steam injected gas turbine(STIG) cycle. The effects of pressure ratio, turbine inlet temperature and specific mass flow rate of steam per kg of air used in the thermodynamic analysis of steam injected gas turbine(STIG) cycle on thermal efficiency of the cycle, specific work output and specific fuel consumption have been investigated. From the results obtained in graphs it is observed that thermal efficiency of steam injected gas turbine(STIG) cycle increases and net work output increases and specific fuel consumption decreases as pressure ratio increases; thermal efficiency of steam injected gas turbine(STIG) cycle and specific work output increases with increase in turbine inlet temperature. Results also show that STIG cycle efficiency is always greater than simple gas turbine cycle for same pressure ratio and turbine inlet temperature and for wide range of parameters STIG cycle is superior to simple gas turbine cycle. In STIG cycle as specific mass flow rate per kg of air increases cycle efficiency and net work output also increases.

Keywords: *Gas Turbine Cycle; Steam Injection; HRSG, Energy Analysis.*

1.0 Introduction

There are three main types of fossil fuels; coal, oil and natural gas. After food, fossil fuel is humanity's most important source of energy. Liquid fuels such as oil and natural gas are the slowest growing energy source, and their consumption is projected to increase at an annual rate of 1.2 percent from 2005 to 2030. Nonetheless, world demand for oil is projected to increase 37% over 2006 levels by 2030 (118 million barrels per day from 86 million barrels per day).

This increase is mainly due to projected increases in oil demand for transportation and increasing demand for energy in developing countries.Fossil fuels provide around 66% of the world's electrical power, and 95% of the world's total energy demands (including heating, transport, electricity generation and other uses). Coal provides around 28% of energy, oil provides 40% and natural gases provide about 20%.The various studies show that the depletion of fossil fuels being a huge problem facing the world at this time. As fossil fuels are coming to a shortage and measures are be taken in order to conserve the irreplaceable energy resources.Therefore there is a huge requirement to use these fuels efficiently by using new technologies. Large amount of fuel is also used in producing the electricity by Gas Turbines.

So, it is necessary to improve the efficiency of conventional gas turbine by introducing new technologies like reheating, regenerating, inter-cooling, steam injection, water injection, regenerative steam injection etc. By the above mentioned methods we can produce more electricity by consuming less fuel. The injection of steam into the combustor chamber of the gas turbine engines was a recurrent research topic as a mean of reducing the atmospheric emissions of NOx. The objective of the steam injection at the combustor is to reduce.

molecular oxygen formed at high temperatures. Fundamental research on steam injection at the combustion chamber to reduce NOx emissions identified the steam-to-fuel ratio as the main parameter affecting the amount of reduction of NOx emissions. Further, gas turbine is very compact as compared to water and steam turbines. Serious development of gas turbine began not along before

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the second World war with shaft power in mind, but the emphasis was soon diverted to the turbojet engine for aircraft propulsionThe use of gas turbines is increasing for producing electricity, operating airplanes and for various industrial applications such as, nuclear power plant (NPP), and the petroleum power plant.

In the last three decades, improvements in gas turbines have shown their success in increasing the amount of energy output from power stations.

The basic gas turbine cycle has low thermal efficiency which decreases in the hard climatic conditions of operation, so it is important to look for improved gas turbine based cycles.

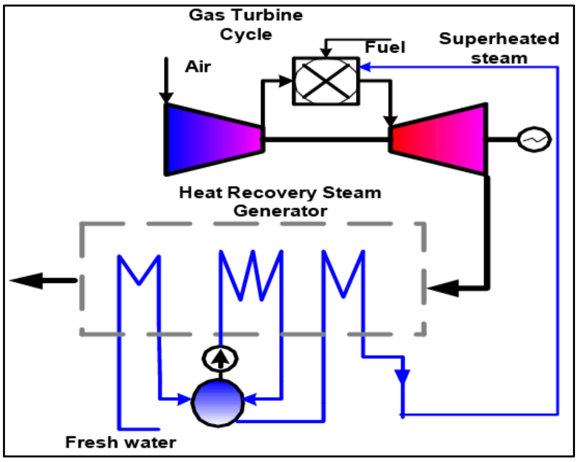
The gas turbine's performance is highly dependent on ambient temperature which varies considerably between the day and the night, the summer and the winter. The power that it yields, in particular, decreases considerably as ambient temperature increases. Industrial gas turbines are one of the well established technologies for power generation. Various additional cycle configurations such as reheating, regeneration, intercooling and steam injection have been suggested. All of them offer increased performance and increased output compared to a simple gas turbine cycle. Several types of water or steam injection gas turbine cycle (STIG) have been proposed in previous studies and the performance characteristics of them investigated.

The exhaust gas from the turbine is used as an energy source in a heat recovery steam generator (HRSG) where energy is transferred from the exhaust gases to the boiler feed water. The high pressure steam is generated from HRSG. The steam is then injected into the combustor. Injection of steam increases the mass flow rate through the expander and so the power output and the efficiency of the turbine increase. Steam injection also helps in reducing the NOx emissions from the gas turbine.

The amount of steam generated in the HRSG depends upon the pinch point of the boiler. Due to this pinch point and the turbine outlet temperature, the HRSG cannot utilize all the heat available in the flue gas to generate steam. The objective of the present work is to improve the performances of gas turbine by injecting suitable quantities of steam in the combustion chamber. As per recently carried out several tests shows that this new device utilizing steam injection can improve some key performance parameters for output, thermal efficiency and emissions.

2.0 System Description

Fig 1: STIG Cycle



The STIG (Steam Injected Gas Turbine) cycle is a gas turbine cycle in which the steam is generated in heat recovery steam generator at low pressure and then pressurized to introduction into gas turbine.Steam Injected Gas Turbine (STIG) systems operate as an enhancement to the simple gas turbine cycle. High quality steam is used to increase the power output and improve operating efficiency of the simple gas turbine cycle. Steam is typically produced by heat recovery heat generator (HRSG), external steam source or external process source and then injected into the combustion chamber of the gas turbine. The site at which this steam is injected differs according to the design of the particular gas turbine; however, in principal high pressure steam is injected into the high-pressure sections of the GT via the combustor fuel nozzles and compressor discharge plenum.

In its most basic form, the steam injected in the combustion chamber works by increasing mass flow in the turbine. The increased mass flow generates an increase in the rotational torque and power output. Normally, as mass flow through the power turbine increases so to does the mass flow through the compressor stages. While this power increase is beneficial, it is offset by an increase in parasitic load due to the compression of increased air coming into the Gas Turbine.

The beauty of the Steam Injected Gas Turbine (STIG) process lies in its ability to increase the mass flow in the power turbine without increasing the mass flow through the compressor stages. Steam Injected Gas Turbine (STIG) uses high pressure dry steam compresses and injects this steam after the compressor. Thus it bypasses the compressor stage increasing the power generated in the turbine stages without increasing the resulting compression loads. A heat recovery steam generator or HRSG is an energy recovery heat exchanger that recovers heat from a hot gas stream. It produces steam that can be used in a process or used to drive a steam turbine. A common application for an HRSG is in a Steam Injected Gas Turbine Cycle (STIG) Power Plant, where hot exhaust from a gas turbine is fed to an HRSG to generate steam which is fed into the combustor. This combination produces electricity more efficiently than either the gas turbine or steam turbine alone. Another application for an HRSG is in diesel engine combined cycle power plants, where hot exhaust from a diesel engine is fed to an HRSG to generate steam which in turn drives a steam turbine. The HRSG is also an important component in cogeneration plants. Cogeneration plants typically have a higher overall efficiency in comparison to a combined cycle plant. This is due to the loss of energy associated with the steam turbine.

3.0 Thermodynamic Analysis

The pressure ratio of compressor is $r_p = \frac{P_2}{P_1}$

Heat balance equation for Combustion chamber is given by

$$(1+f+s)C_{pg}(T_3 - T_2) = (f \times C.V.) + (s \times h_{fs}) \quad (1)$$

Heat balance equation for HRSG is

$$(m_a + m_s)C_{pg}(T_4 - T_{PG}) = m_s(h_g - h_f) \quad (2)$$

Process heat in HRSG is

$$Q_p = m_s(h_g - h_c) \ \& \ Q_p = (m_a + m_s)C_{pg}(T_4 - T_5) \quad (3)$$

Turbine work is $Wt = (1+f+s)C_{pg}(T_3 - T_4)$ (4)

Compressor is $Wc = C_{pa}(T_2 - T_1)$ (5)

Heat supplied is $Q_s = f \times C.V. \times \eta_{cc}$ (6)

Specific net work output is $W_{net} = W_T - W_C$ (7)

Efficiency of cycle is $\eta_{cycle} = \frac{W_{net}}{Q_s}$ (8)

SFC is $sfc = \frac{3600}{\eta_{cycle} \times C.V. \times \eta_{cc}}$ (9)

Specific fuel rate per unit mass of air flow rate is given as f and specific steam rate per unit air flow rate is given as s. This thermodynamic analysis is done by using Engineerin Equation Solver(EES).

4.0 Results and Discussions

The effect of parameters such as pressure ratio, Turbine Inlet Temperature(TIT) and specific flow rate of steam per kg of air have been studied on gas turbine performance parameters such as cycle efficiency, specific work output and specific fuel consumption of both STIG and simple gas turbine cycles. The pressure ratio is varied upto 40 and TIT is varied between 1100 K and 2000 K. the effect of above parameters. Specific steam flow rate per kg of air is varied between 0.1 and 0.4.

4.1 Effect of pressure ratio

The effect pressure ratio on performance parameters is shown in Fig 2 - 4. In both STIG and simple gas turbine cycle as the pressure ratio increases cycle efficiency also increases. But the cycle efficiency of STIG cycle is always more than simple GT cycle for same pressure ratio at a given TIT. Specific net work output increases initially as pressure ratio increases but later it starts decreasing in both STIG and simple GT cycles. STIG cycle develops more net work output as compared to simple GT cycle at the same pressure ratio. In case of STIG cycle net work output increases as specific steam flow rate per kg of air. In both STIG and simple GT cycle as the pressure ratio increases sfc decreases. The decrease in sfc of STIG cycle is less while compared to simple GT cycle at the same pressure ratio.

4.2 Effect of turbine inlet temperature(TIT)

The effect of Turbine Inlet Temperature(TIT) on performance parameters is shown in Fig 5 – 7. In simple GT cycle as the TIT increases cycle efficiency also increases. But in case of STIG cycle at lower specific steam flow rate cycle efficiency increases as TIT increases and at higher specific steam flow rate cycle efficiency decreases as TIT increases. It is observed that efficiency of STIG cycle is always more than simple GT cycle for same TIT at a given pressure ratio. In both STIG and simple GT cycles as TIT increases net work output also increases. As specific steam flow rate in STIG cycle increases net work output also increases for the same TIT. The net work output of STIG cycle is always more than simple GT cycle for same TIT at a given pressure ratio. In simple GT cycle as the TIT increases sfc decreases. But in case of STIG cycle at lower specific steam flow rate sfc decreases as TIT increases and at higher specific steam flow rate sfc increases as TIT increases. The sfc of STIG cycle is always lower than simple GT cycle for same TIT at a given pressure ratio.

4.3 Effect of specific steam rate per kg of air

The effect of specific steam rate per kg of air on performance parameters is shown in Fig 8 – 9. In As specific steam flow rate per kg of air increases both cycle efficiency and net work output of STIG cycle also increases.

Fig 2: Effect of Pressure on Cycle Efficiency (at TIT 1500K)

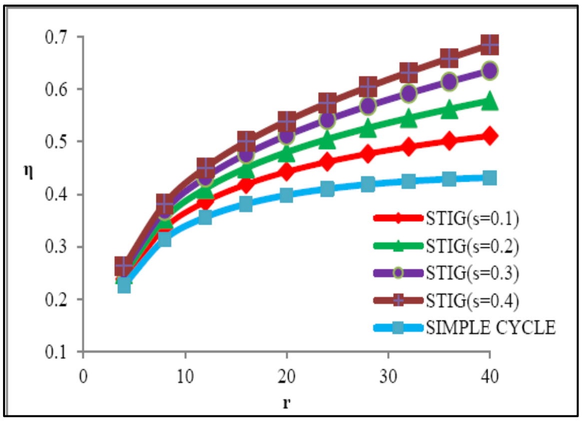


Fig 3: Effect of Pressure on Specific Work Output (at TIT 1500K)

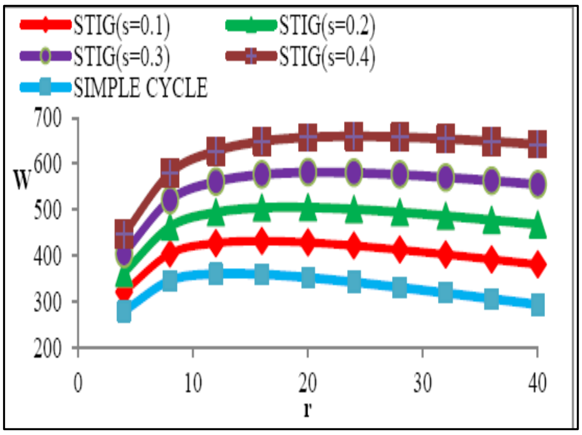


Fig 4: Effect of Pressure on sfc (at TIT 1500K)

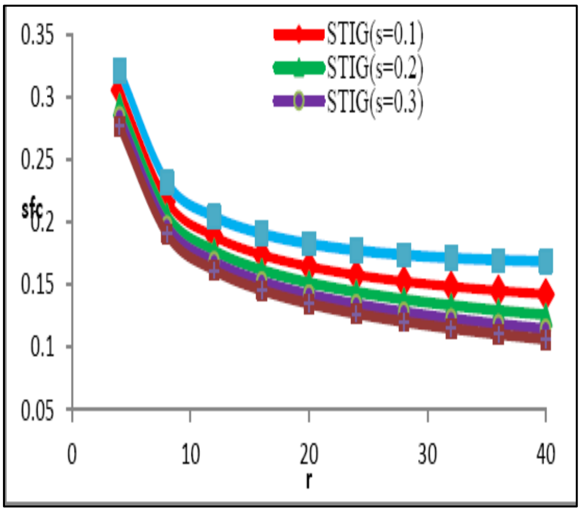


Fig 5: Effect of TIT on cycle efficiency (at rp 12)

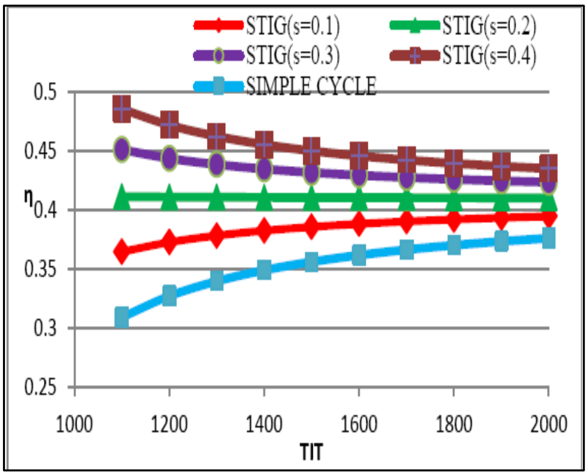


Fig 6: Effect of TIT on Specific Work Output (at rp 12)

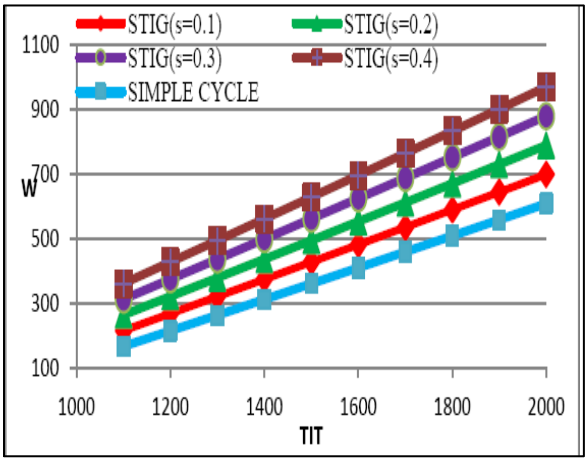


Fig 7: Effect of TIT on sfc (at rp 12)

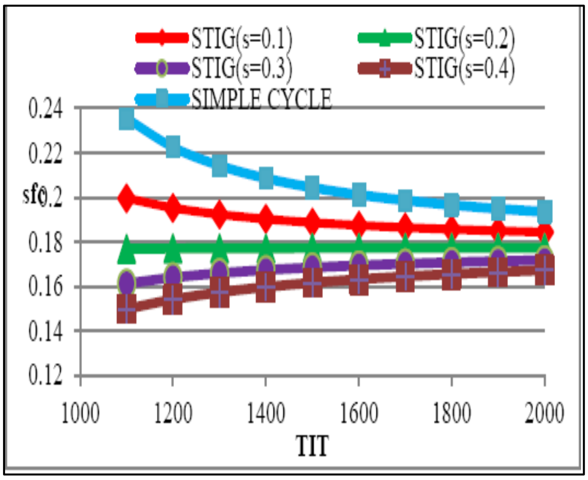


Fig 8: Effect of Specific Steam Rate Per kg of Air on Cycle Efficiency (at rp 12; TIT 1500 K)

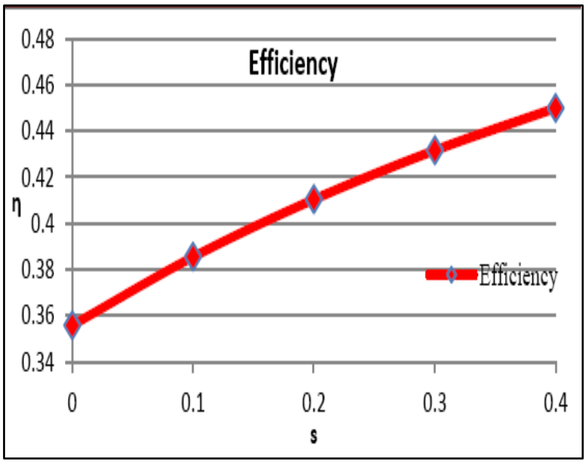
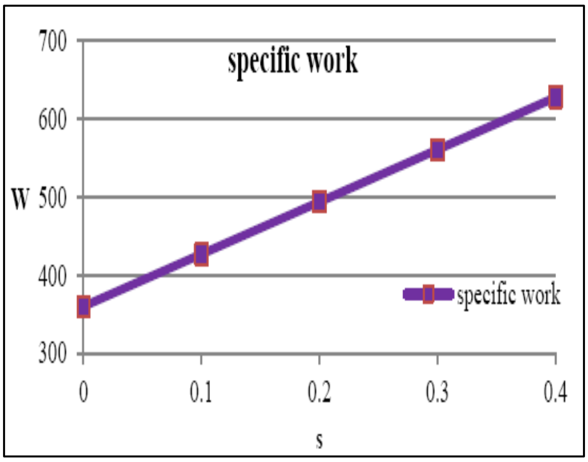


Fig 9: Effect of Specific Steam Rate Per kg of Air on Specific Work Output (at rp 12; TIT 1500 K)



6.0 Conclusions

Thermodynamic analysis os Steam Injected Gas Turbine (STIG) cycle has been studied and compared with simple Gas Turbine (GT) cycle with wide range of parameters of pressure ratio, Turbine Inlet Temperature and specific steam flow rate per kg of air on gas turbine performance parameters such as cycle efficiency, specific work output and specific fuel consumption. From the results of these studies following conclusions are obtained:

- For wide range of parameters STIG cycle is superior to simple GT cycle
- As pressure ratio increases cycle efficiency and net work output also increases but sfc decreases
- As TIT increases efficiency and net work output of simple GT cycle also increase. For STIG cycle as TIT increases net work output also increases as increase in specific steam flow rate but efficiency of STIG cycle decreases with increase in TIT at higher specific steam flow rate per kg of air.
- In all value of specific steam rates, sfc of STIG cycle is always lower than simple GT cycle for a given pressure ratio and TIT.
- In STIG cycle as specific steam flow rate increases cycle efficiency and net work output also increase.

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Nomenclature

C.V.	Calorific value of fuel
C_p	specific heat, J. kg-1. K-1
W s	Specific work output Specific srean rate per kg of air
Sfc T	Spefic fuel consumption Temperature
Greek symbols	
η	Cycle efficiency
Subscripts	
g	gas
f	fluid (pure water)
a	Air