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Analysis of a Regenerative Gas Turbine Cycle for Power Plant

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Abstract: The deregulation of the electric power market introduced a strong element of competition. Power plant operators strive to develop advanced operational strategies to maximize the profitability in the dynamic electric power market. New methodologies for gas turbine power plant operational modeling and optimization are needed for power plant operation to enhance operational decision making, and therefore to maximize power plant profitability by reducing operations and maintenance cost and increasing revenue. In the present work, the evaluation of an improved method for analysis of thermodynamic performance in gas turbine engines has been performed. A regenerator of a gas turbine cycle is considered for multi-criteria optimization. Different regenerator effectiveness for optimization of the proposed cycle has been considered. The effects of regenerator effectiveness, turbine inlet temperature, ambient temperature and compression ratio have been proposed to select optimum configuration for gas turbine and its effect on the cycle performance. The analysis performance code has been performed used the C++ software and the graphs plotted in Origin 6.1. The simulating code for gas turbine configuration results show that the simple gas turbine configuration is more suitable with regards to power output, but the regenerative gas turbine configuration has higher efficiency with the effect ambient temperature. The simple gas turbine configuration has higher power output with effect the compression ratio, while the regenerative gas turbine configuration has higher efficiency with effect lower compression ratio, therefore the variation of total power output is insignificance at lower compression ratio. The extensive modelling performed in this study reveals that, the ambient temperature and compression ratios are strongly influence on the performance of combined cycle.

Keywords: Gas Turbine, Regeneration, Thermal Efficiency, Power Plant, Brayton Cycle.

I. INTRODUCTION

The gas turbine obtains its power by utilizing the energy of burnt gases and air, which is at high temperature and pressure by expanding through the several ring of fixed and moving blades. To get a high pressure of working fluid, which is essential for expansion a compressor, is required. The quantity of the working fluid and speed required are more, so, generally, a centrifugal or an axial compressor is employed. The turbine drives the compressor and so it is coupled to the turbine shaft. If after compression the working fluid were to be expanded in a turbine, then assuming that there were no losses in either component the power developed by the turbine would be just equal to that absorbed by the compressor and the worked on would be zero. But increasing the volume of the working fluid at constant pressure, or alternatively increasing the pressure at constant volume can increase the power developed by the turbine.

The common types of turbines, which are in use, are axial flow type. The basic requirements of the turbines are light weight, high efficiency; reliability in operation and long working life. Large work output can be obtained per stage with high blades speeds when the blades are designed to sustain higher stresses. More stages of the turbine are always preferred in gas turbine power plant because it helps to reduce the stresses in the blades and increases the overall life of the turbine. More stages are further preferred with stationary power plants because weight is not the major consideration in the design which is essential in aircraft turbine-plant. Performance of a gas turbine (GT) has strong dependence of climate conditions [4]. A suitable solution to minimize this negative effect is to raise inlet turbine temperature and reduce temperature of inlet air to GT compressor. Combined cycles gas turbines (CCGT) are a lot used to acquire a high-efficiency power plant. Increases the peak compression ratio has been proposed to improve the combined-cycle gas-turbine performance. The code of the performance model for CCGT power plant was developed utilizing the MATLAB software.

The simulating results show that the overall efficiency increases with the increase of the peak compression ratio. The total power output increases with the increase of the peak compression ratio. The peak overall efficiency occurs at the higher compression ratio with low ambient temperature and higher turbine inlet temperature. The overall thermal efficiencies for CCGT are higher compared to gas-turbine plants [7].

II.MODELLING OF COMPONENTS

A. Gas Model

The thermodynamic properties of air and products of combustion are calculated by considering variation of specific heat and with no dissociation. Table containing the values of the specific heats against temperature variation have been published in many references. The curve fitting the data is used to calculate specific heats, specific heat ratio, and enthalpy of air and fuel separately from the given values of temperature. Mixture property is then obtained from properties of the individual component and fuel air ratio (FAR).

1. If $T_a \leq 800$

$$c_{pa} = (1.0189 \times 10^3) - (0.13784.T_a) + (1.9843 \times 10^{-4}.T_a^2) + (4.2399 \times 10^{-7}.T_a^3) - (3.7632 \times 10^{-10}.T_a^4) \quad (1)$$

2. If $T_a > 800$

$$c_{pa} = (7.9865 \times 10^2) + (0.5339.T_a) - (2.2882 \times 10^{-4}.T_a^2) + (3.7421 \times 10^{-8}.T_a^3) \quad (2)$$

In the above equations, T stands for gas or air temperature in deg K and $t = \frac{T}{100}$.

B. Gas Turbine analysis with Regeneration

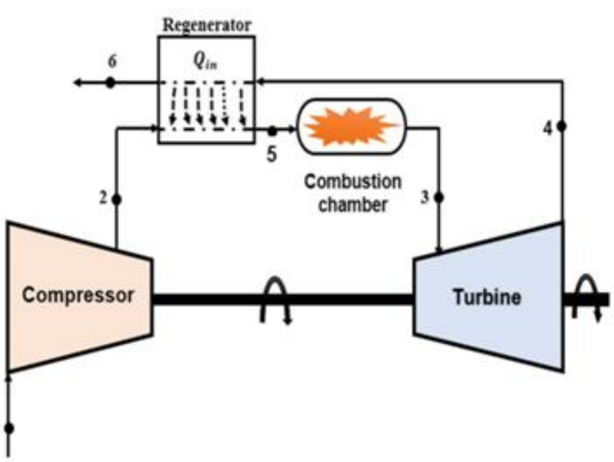

Fig1: Schematic of a regeneration gas turbine.

A regenerator is modeling as shows a gas to gas a counter flow heat exchanger fig.1. In this, extracts heat from the turbine exhaust gas to preheat the compressor discharge air to temperature equal to head of the combustor. As a result, the temperature rise in the combustor is reduced to $T_3 - T_C$, a reduction reflected in a direct decrease in fuel consumed. The following are the assumption for modeling of a regenerator:

- A concept of effectiveness of the regenerator is included to account for its inefficiencies.
- There is a pressure drop in the stream passing through the regenerator, which is taken as percentage of inlet pressure.

Fig.2 shows the T-s diagram for regenerative gas turbine cycle. The actual processes and ideal processes are represented in dashed line and full line respectively.

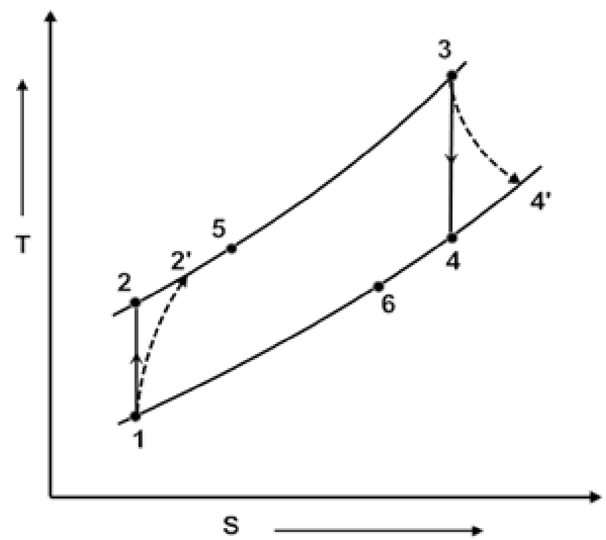

Fig2: T-s Diagram of gas turbine cycle with Regeneration.

These parameters in terms of temperature are defined as:

$$\eta_C = \frac{T_2 - T_1}{T'_2 - T_1} \quad (3)$$

$$\eta_t = \frac{T_3 - T'_4}{T_3 - T_4} \quad (4)$$

The regenerator effectivenesscan be written as:

$$\varepsilon_{rc} = \frac{T_5 - T'_2}{T'_4 - T'_2} \quad (5)$$

The work required to run the compressor is expressed as:

$$W_c = C_{pa}.T_1 \left[\frac{r_p^{\frac{\gamma_a - 1}{\gamma_a}} - 1}{\eta_c} \right] \quad (6)$$

The work developed by turbine is then rewritten as:

$$W_t = C_{pg}.T_3.\eta_t \left[1 - \frac{1}{r_p^{\frac{\gamma_g - 1}{\gamma_g}}} \right] \quad (7)$$

Where turbine inlet temperature (TIT) $= T_3$

The net work is expressed as:

$$W_{net} = C_{pg} \cdot T_3 \cdot \eta_t \left[1 - \frac{1}{r_p^{\frac{\gamma_g - 1}{\gamma_g}}}\right] - C_{pa} \cdot T_1 \left[\frac{r_p^{\frac{\gamma_a - 1}{\gamma_a}} - 1}{\eta_c}\right] \quad \textbf{(8)}$$

Power output is given by:

$$P = \dot{m}_a \times W_{net} \quad \textbf{(9)}$$

Air to fuel ratio is given by:

$$AFR = \frac{LCV_f}{Q_{add}} \quad \textbf{(10)}$$

And specific fuel consumption

$$SFC = \frac{3600}{AFR \cdot W_{net}} \quad \textbf{(11)}$$

III. RESULTS AND DISCUSSION

The analyses of the present work have been carried out by developing software in C++ program using thermodynamic laws. The results are plotted in menu driven software Origin 50 for prediction of the thermal cycle. The present work has been divided in two major parts. First the analysis for regenerative gas turbine cycle and the second one is for reheating cycle. In both the cases, the overall pressure ratios and turbine inlet temperatures are taken differently. Expansion of the gases in turbine takes place after reaching the temperature equal to the inlet temperature of high pressure turbine. The pressure drop (2%) also considered in both the combustor. The variable regenerative effectiveness (0.5 to 0.9) has been considered for the cycle analysis. Fig 3 shows the variation of thermal efficiency

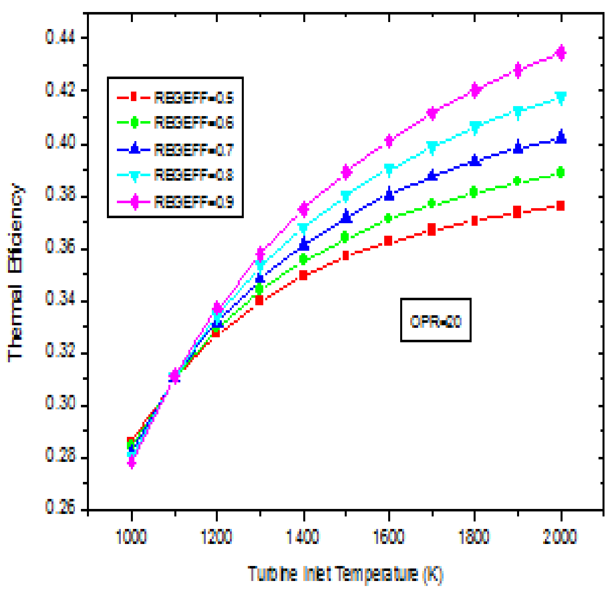

Fig3: Thermal efficiency vs Turbine inlet temperature.

with turbine inlet temperature for various regenerative effectiveness at a given overall pressure ratio. It has been observed that the thermal efficiency increases on increasing the turbine inlet temperature for a given regenerative effectiveness but at a very low TIT i.e. about 1000 K, the efficiency is slightly lower at high regenerative effectiveness.

Fig 4 shows the variation of specific fuel consumption with turbine inlet temperature for different regenerative effectiveness at a given overall pressure ratio. It has been observed that the specific fuel consumption decreases on increasing the turbine inlet temperature for a given regenerative effectiveness But at a very low TIT i.e. about 1000-1100K, the specific fuel consumption is slightly higher at high regenerative effectiveness. On the other hand, the specific fuel consumption decreases on increasing the regenerative effectiveness for a given TIT.

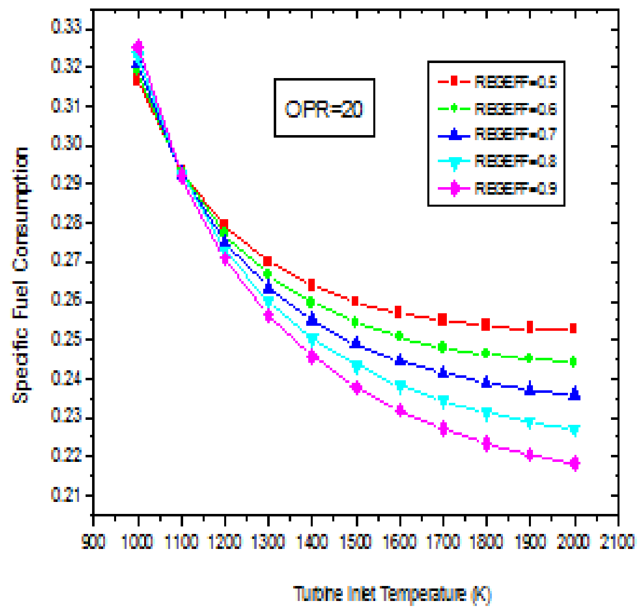

Fig4 Specific fuel consumption vs turbine inlet temperature.

Fig 5 represents the variation of mass of fuel in combustor with regenerative effectiveness at different turbine inlet temperature at a given overall pressure ratio. It has been found that the mass of fuel in combustor decreases on increasing regenerative effectiveness for a given turbine inlet temperature. But at a very low TIT i.e. about 1000-1100K, the mass of fuel in combustor is increases on increasing the regenerative effectiveness. Figure 6 represents the variation of thermal efficiency with regenerative effectiveness at different overall pressure ratio at a given turbine inlet temperature. It has been found that the thermal efficiency increases on increasing the regenerative effectiveness. This rate of increase is more at lower OPR (i.e. 10-15) but at higher OPR the rate of increase is quite significant. The maximum thermal efficiency has been observed at 15-20 OPR.

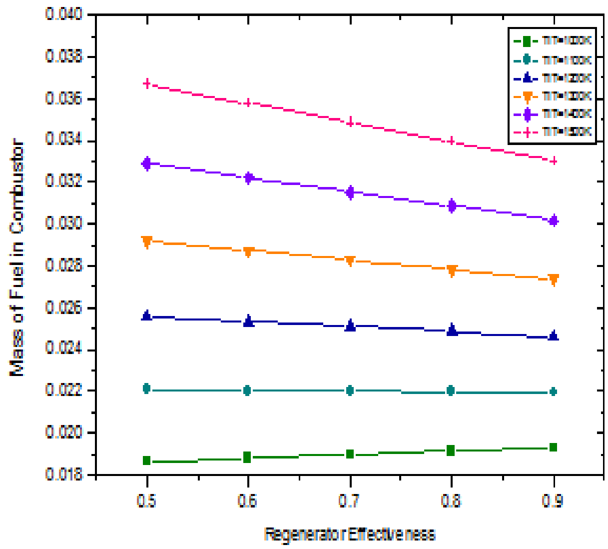

Fig5: Mass of fuel in combustor vs. regenerative effectiveness.

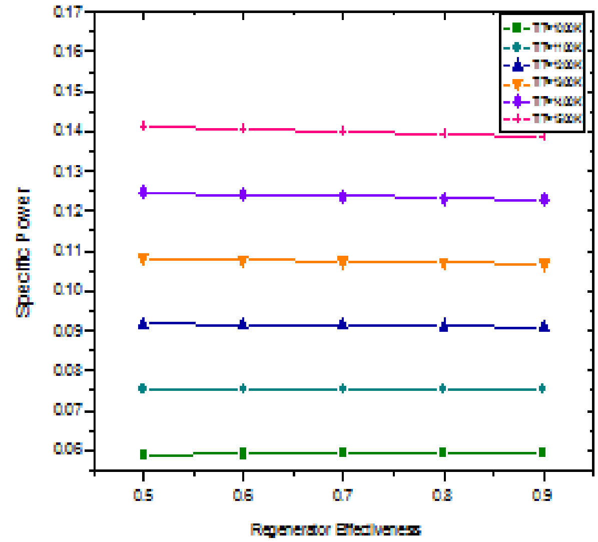

Fig7: Specific power vs. regenerative effectiveness.

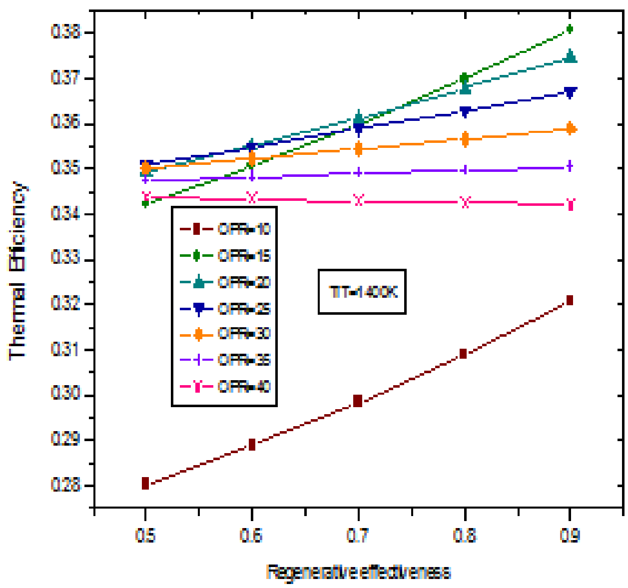

Fig6: Thermal efficiency vs regenerative effectiveness.

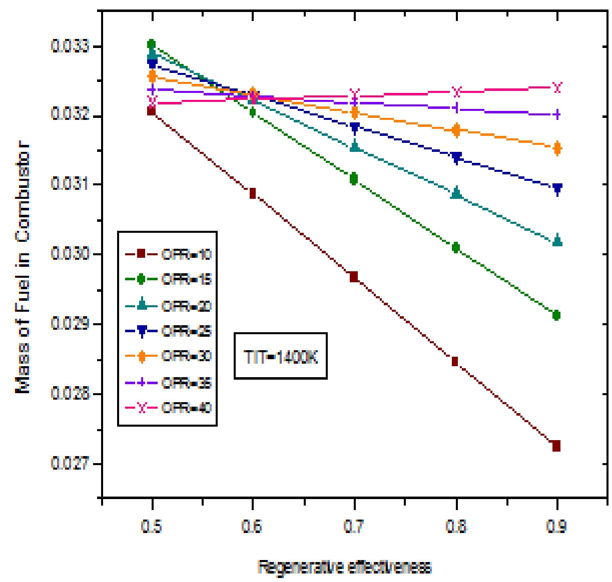

Fig8: Mass of fuel in combustor vs. regenerative effectiveness.

Fig 7 represents the variation of Specific power with regenerative effectiveness at different turbine inlet temperature at a given overall pressure ratio. It has been found that the Specific power is higher for high turbine inlet temperature. Fig 8 represents the variations between mass of fuel required in the combustor with regenerative effectiveness for different overall pressure ratio. The mass of fuel required in the combustion chamber is decreases on increasing the regenerative effectiveness for a given OPR. It has also been found that the mass of fuel required is almost constant for higher range of OPR. Therefore, the lowest fuel required at low OPR.

Fig 9 represents the variations between specific powers with regenerative effectiveness for different overall pressure ratio. The specific power decreases on increasing the regenerative effectiveness for a given OPR. It has also been found that the specific power is higher for the higher range of OPR. Fig 10 represents the variations of specific fuel consumption with regenerative effectiveness for different overall pressure ratio. The specific fuel consumption is minimum at optimum value of OPR for high regenerative effectiveness.

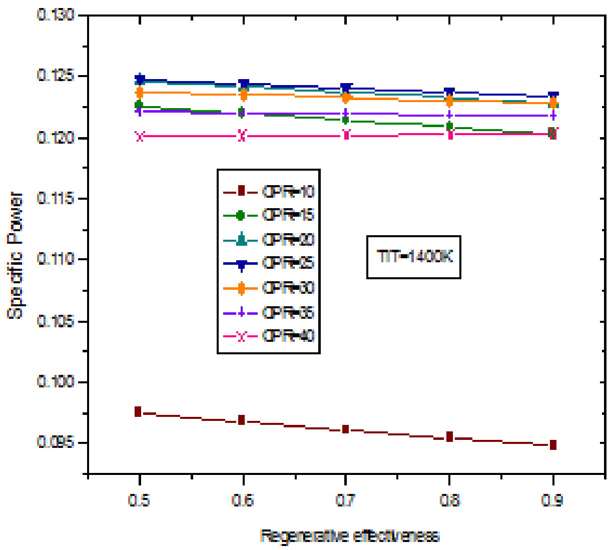

Fig9: Specific power vs. regenerative effectiveness.

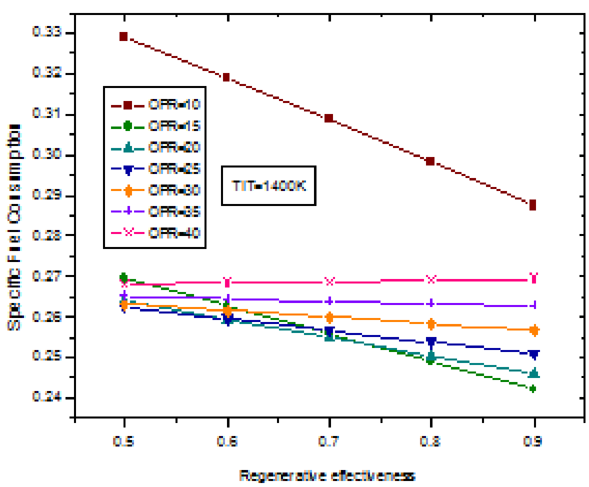

Fig10: Specific fuel consumption vs. regenerative effectiveness.

IV. CONCLUSION

The thermal analysis of the gas turbine cycle for two different arrangements is analyzed. The regenerative cycles with regenerative effectiveness (0.5 t0 0.9) and the reheat cycle (reheat temperature equal to the high pressure turbine inlet temperature) have been taken for the analysis. Both the thermal cycles concentrate to increase the thermal efficiency. The thermal efficiency is high for higher regenerative effectiveness under the application of high range of turbine inlet temperature (above 1100K). The specific fuel consumption is also low for an effective regenerator. The regenerative cycle also reveal that the overall pressure ratio should be in the range of 15 to 20 for better cycle performance. For the higher range of OPR and for a very low OPR, the results are not good.

Tamb / TA	Ambient temperature (K)
P	Pressure
T	Temperature
TSFC	Thrust Specific Fuel Consumption
GAMMA.	Specific Heat Ratio for air
GAMMAG	Specific Heat ratio for gas
OPR	Overall Pressure Ratio
CPA	Specific Heat of Air
CPG	Specific Heat of Gas
MFB	Mass of Fuel in Combustion
EFF	Chamber
WT	Thermal Efficiency
WC.	Turbine Work
FAR.	Compressor Work
AR	Fuel Air ratio
SP	Air Rate
WR	Specific Power
SFC	Work Ratio
NETP	Specific Fuel Consumption
ETAGEN	Net Power
RGEFF	Efficiency of Generator
QA	Regenerator Efficiency
ETAT	Heat Input
Pamb / PA	Turbine Efficiency
R	Ambient Pressure (bar)
ETAC	Gas Constant for Air
RG	Compressor Efficiency
ETAM	Gas Constant for Gas
MA	Mechanical Efficiency
ETAB	Mass of air flow (kg/s)
CV	Combustion Chamber Efficiency
TIT	Calorific Value (kJ/kgK)
	Turbine Inlet Temperature (K)

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