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Performance Investigation of Combined Cycle Gas Turbine under Varying Operating Conditions

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ABSTRACT: Combined Cycle Gas Turbine is used to achieve higher thermal efficiency and utilisation of energy efficiently by minimizing the energy loss. Gas Turbine as topping cycle integrated with steam turbine as bottoming cycle is generally named as combined cycle gas turbine (CCGT). In this paper, the performance of the CCGT is investigated thermodynamically using MATLAB coding technique under varying operating parameters such as Compression Pressure ratio, Compressor inlet temperature, Turbine inlet temperature and Air Fuel ratio. The extreme overall efficiency occurs at the higher compression pressure ratio with low compressor inlet temperature and higher turbine inlet temperature, while, the overall thermal efficiencies for CCGT are higher compared to the individual thermal efficiencies of the gas turbine and steam turbine power plants. The total power output raise with an increase of cycle peak temperature ratio and decrease of the compression pressure ratio.

KEYWORDS: Gas turbine, Steam Turbine, CCGT, Overall thermal efficiency.

I. INTRODUCTION

Energy is a vital requirement for human existence, and thus a propelling force of civilization as almost all of our daily activities and productive processes involve energy in one form or another. The demand for energy throughout the world is increasing rapidly due to growth in population, enhancing living standards and emphasis on producing energy intensive industries in almost all newly developing countries to boost their economies in order to overcome poverty.

In order to balance the energy demand various technologies are available, Among combined cycle gas turbine (CCGT) technology has attracted much attention by the scientific researchers in the last few decades by employing the Brayton cycle gas turbine and Rankine cycle steam turbine with air and water as working fluids to achieve efficient, reliable, and economic power generation. Currently overall thermal efficiencies up to 60% are confirmed by the foremost manufacturers from the sector as state of the art and special modifications have been proposed to improve the overall thermal efficiencies more than 65% can be achieved by incorporating enhancements in the gas turbine technology such as higher compression ratio, turbine inlet temperature and compression inlet condition. The improvement in HRSG design, the use of advanced thermodynamic plant configurations such as two shaft gas turbine, combining intercooler cycle and regenerative cycle may also be adopted to improve the thermal efficiency

II. LITERATURE SURVEY

As per the survey made by the scientists by the year 2050 fossil fuels are going to be depleted completely. This made the scientists to concentrate on improving the efficiency of the existing system by hybrid technologies. The simple

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CCGT power plant is one of the world's most efficient fossil fuel to electricity converters. The gas turbine is mechanical power-producing engines in industry. The main characteristic of a gas turbine which differentiates from remaining is its working. Thermodynamic processes such as compression, combustion, and expansion are performed in individual components like compressor, combustion chamber, and turbine. Combined Cycle Gas Turbine Power Plants (CCGT) and related technologies have been mature sufficient attributable almost 45 years of experience and carrying out in power generation field. The design of CCGT power plants is intrinsically complex due to two different power cycles mediating by HRSG. The performance of the entire system rigidly depends on the optimal incorporation between the power units.

The foremost HRSG equipped in CCGT plants is single pressure level used in small medium power generation (60-70 MW) and seldom in plants of size over 100 MW. Second pressure levels HRSG came into existence in the second half of the 1980s characterized a new industrial development that has led at the end of the last century to the introduction of systems with 3 pressure levels with re-heater. Based on mode of working, CCGT power plants it appears about two-thirds of the total power is generated by the gas turbine cycle and one-third by the steam turbine cycle so the reference value of the power output of the gas turbine is of 200 MW. The Maximum pressure of the HRSG ranges from 120 and 165 bars. Most of the installed CCGT power plant used the outlet temperature of the gas turbine around 850 K

III. METHODOLOGY AND DISCUSSIONS

A CCGT integrated with Joule cycle as topping cycle and Rankine cycle as bottoming cycle is considered in the current study and analysis. A gas turbine power plant mainly consists of four components, compressor, combustion chamber, turbine and generator. The compressor takes air from atmosphere and the compressed air conveyed to the combustion chamber, where the Liquid or gaseous fuel is commonly ignited to increase the temperature of compressed air by combustion process. High temperature gases leaving the combustion chamber expand through turbine which produces work and finally discharges to the atmosphere. The waste exhaust gas temperature made to flows into the heat recovery steam generator (HRSG), which consists of super heater, evaporator and economizer. This makes HRSG to supply steam for the steam turbine in order to produce electricity. Latter, the waste condensate from the steam turbine will be flowed into a condenser, where cooling water transfers waste heat to the cooling tower. In the last stage, feed water from a condenser, this is suctioned by the feed water pump and sent to the HRSG and cycle repeats.

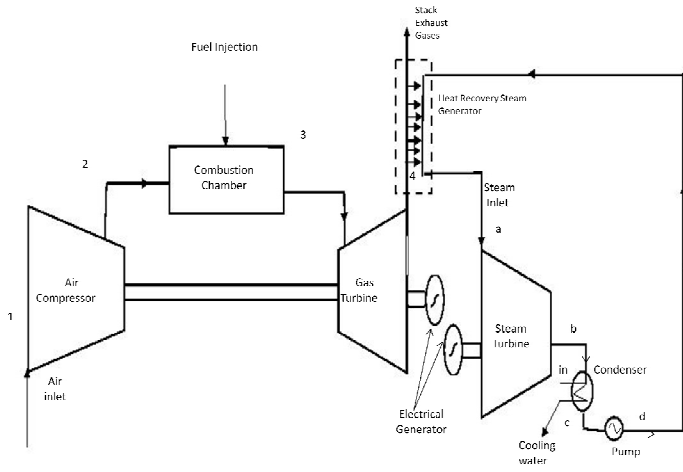


Fig.(1) Schematic diagram of combined cycle gas turbine plant

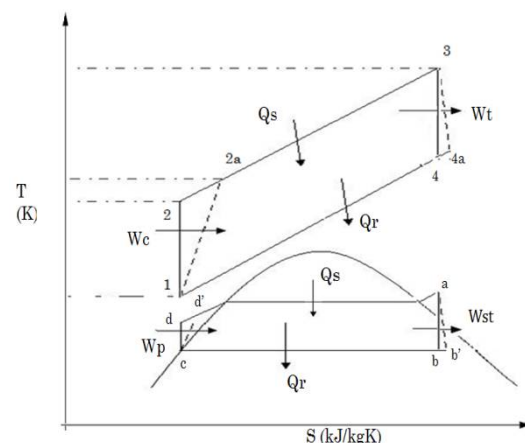


Fig.(2) Temperature – Entropy Diagram

Process: - Gas Turbine Cycle: 1-2-3-4

Steam Turbine Cycle: a-b-c-d

Gas Turbine Joule Cycle Model consists of gas turbine, also named as combustion turbine having upstream rotating compressor coupled to a downstream turbine, and a combustion chamber in-between. Fresh atmospheric air flows through a compressor to compress it to higher pressure. Energy is then added by spraying fuel into the air and igniting causes to high temperature gas. This high-temperature high-pressure gas enters a turbine, where it expansion of gas

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takes place and reaches exhaust pressure, producing a shaft work output in the process. For the success of a GT power plant, efficient compression of large air volume is important. The axial flow compressor and the centrifugal compressor are the two main types of compressors. In order to obtain adequate air through the diameter of the compressor, most of the power plants have design compressors. The new design of the compressor has the ability to retain comparatively high efficiency and aerodynamic stability over the operating range together with minimum stages.

Equation (1) defines the compressor pressure ratio (r)

$$r = \frac{p_2}{p_1} \quad (1)$$

Where p_1 and p_2 denotes compressor inlet and outlet air pressure, respectively

Equation (2) presents an isentropic efficiency for compressor,

$$E_c = \eta_c = \frac{T_2 - T_1}{T_{2a} - T_1} \quad (2)$$

Where T_2 denotes isentropic temperature of compressor, at outlet where as compressor inlet and actual outlet air temperature are expressed by T_1 and T_{2a} respectively.

Equation.(3) is used for calculating the actual compressor outlet temperature:

$$T_{2a} = T_1 \left[1 + \frac{r^{\frac{\gamma-1}{\gamma}} - 1}{\eta_c} \right] \quad (3)$$

Where $\gamma = 1.4$, $\gamma_g = 1.33$

Equation (4) expresses the calculation of the compressor work (W_c) without taking blade cooling into account:

$$W_c = \frac{C_{pa} \times (T_{2a} - T_1)}{\eta_m} \quad (4)$$

Where, η_m is the mechanical efficiency of the compressor and turbine.

While C_{pa} is the specific heat of air which can be built-in by Equation (5) for the range of $200K < T < 800K$.

$$C_{pa} = (1.0189 \times 10^3 - 0.13784 \times T_a + 1.9843 \times 10^{-4} \times T_a^2 + 4.2399 \times 10^{-7} \times T_a^3 - 3.7632 \times 10^{-10} \times T_a^4) \times 10^{-3} \quad (5)$$

Where $T_a = \frac{T_{2a} + T_1}{2}$

Equation (6) presents an isentropic efficiency for turbine,

$$E_t = \eta_t = \frac{T_3 - T_{4a}}{T_3 - T_4} \quad (6)$$

where T_4 denotes isentropic temperature of turbine outlet, whereas actual turbine inlet and outlet temperature are expressed by T_3 and T_{4a} respectively.

Equation (7) is used for calculating turbine outlet temperature

$$T_{4a} = T_3 \left[1 - \eta_t \times \left[1 - \frac{1}{r^{\frac{\gamma_g-1}{\gamma_g}}} \right] \right] \quad (7)$$

Equation (8) determine Specific heat of flue gas, (C_{pg})

$$C_{pg} = 1.8083 - 2.3127 \times 10^{-3} \times T + 4.045 \times 10^{-6} \times T^2 - 1.7363 \times 10^{-9} \times T^3 \quad (8)$$

Equation (9) demonstrates the calculation of the work done by the turbine (W_t):

$$W_t = C_{pg} \times (T_3 - T_{4a}) \times \eta_m \quad (9)$$

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Equation (10) gives fuel-air ratio, FAR

$$FAR = \frac{M_f}{M_a} = \frac{C_{pg} \times T_3 - C_{pa} \times T_{2a}}{LCV + C_{pf} \times T_f - C_{pg} \times T_3} \quad (10)$$

Where LCV, C_{pf} and T_f are the lower calorific value, specific heat and temperature of fuel respectively.

Equation (11) illustrate the calculation of the net work done by gas turbine, (W_{GTnet}):

$$W_{GTnet} = W_t - W_c \quad (11)$$

Equation (12) presents mass flow rate of exhaust gas expands through gas turbine denoted by (M_g):

$$M_g = M_f + M_a \quad (12)$$

M_a, M_f air flow rate and flow supplied, respectively

Equation (13) provides Power developed by gas turbine cycle, (P_{GT}):

$$P_{GT} = M_g \times W_{GTnet} \quad (13)$$

Equation (14) determines Heat supplied to gas turbine cycle, (Q_{SGTC}):

$$Q_{SGTC} = C_{pg} \times (T_3 - T_{2a}) \quad (14)$$

Equation demonstrates Gas turbine cycle thermal efficiency, (η_{GTth}):

$$\eta_{GTth} = W_{GTnet} / Q_{SGTC} \quad (15)$$

Steam Turbine Rankine cycle Model where hot flue gases leaving the gas turbine convey in to the HSRG. The waste exhaust gas temperature from gas turbine decreases as it flows into the heat recovery steam generator (HRSG), which consists of superheater, evaporator and economizer. Then the HRSG supplies a steam for the steam turbine to generate electricity. The activities of the subsystems of a steam turbine cycle can be captured in terms of the mass and energy conservation equations, semi-empirical relations and thermodynamic state conservation. In this work, a single pressure heat recovery steam generator (HRSG) is considered here as a common type for the combined cycle gas turbine power plant.

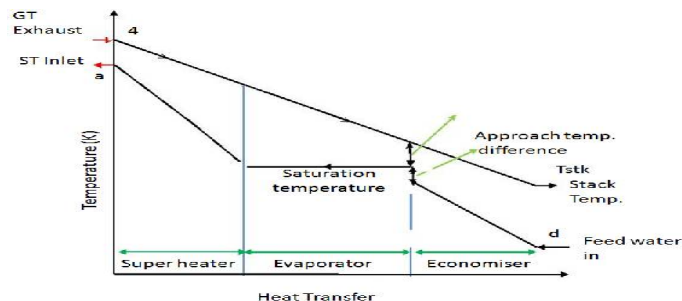


Figure (3) Temperature – Heat transfer diagram for HRSG of Combined Cycle Gas Turbine Plant

Applying the heat balance equations between the gas turbine exhaust and HRSG as given below:

Equation (16) defines Heat supplied to rankine cycle through HRSG,

$$Q_{hrsg} = M_g \times C_{pg} \times (T_{4a} - T_{stk}) \times hf \quad (16)$$

Mass of steam obtained by the energy balance, Equation (17)

$$M_s \times (h_a - h_d) = M_g \times C_{pg} \times (T_{4a} - T_{stk}) \times hf \quad (17)$$

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Where hf is heat loss factor ranges 0.98 to 0.99, T_{4a} is flue gas temperature at HRSG inlet,

h_a, h_d are enthalpy at outlet and inlet of HRSG respectively

T_{stk} is flue gas temperature at HRSG outlet or stack temperature

M_s is steam flow rate, h_b is enthalpy at steam turbine outlet

Equation (18) gives actual work done by steam turbine

$$W_{sta} = M_s \times (h_a - h_b) \times \eta_{ST} \quad (18)$$

Heat Rejected in condenser by Equation (19)

$$Q_{cond} = M_w \times (h_b - h_c) \quad (19)$$

Similarly, Equation (20) gives the actual pump work

$$W_{pa} = (M_w \times v_{fc} \times (P_a - P_b)) / \eta_p \quad (20)$$

P_a, P_b are pressure of steam at steam turbine inlet and condenser respectively

v_{fc} is specific volume at condenser pressure

The net output work of the steam turbine plant provide by Equation (21)

$$W_{STnet} = P_{ST} = W_{sta} - W_{pa} \quad (21)$$

Equation (22) demonstrate thermal efficiency of steam turbine cycle as

$$\eta_{STth} = W_{STnet} / Q_{hrsg} \quad (22)$$

The combined cycle overall thermal efficiency is given by Equation (23)

$$\eta_{STth} = \eta_{GTth} + \eta_{STth} - (\eta_{GTth} \times \eta_{STth}) \quad (23)$$

Total power obtained by Equation (24)

$$TP = P_{st} + P_{GT} \quad (24)$$

List of operating parameters to be varied

- Compression Pressure Ratio
- Turbine inlet Temperature using CPTR
- Compressor air inlet Temperature using CPTR

Where CPTR –Cycle Peak Temperature Ratio

CPTR is defined as the ratio of gas turbine inlet temperature to the compressor inlet temperature.

IV. RESULTS AND DISCUSSIONS

This study provides the characteristics of the overall thermal efficiency, Total power output, for the Single pressure CCGT power plants. The performance of the CCGT affected by the compression ratio, air to fuel ratio, cycle max temperature ratio, isentropic compressor and turbine efficiency of the gas turbine. The effects of these parameters on the power output and efficiency are obtained by the energy-balance utilizing MATLAB code.

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Figure.4 shows the variation of compression pressure ratio, isentropic compressor and turbine efficiencies of the gas turbine cycle on overall thermal efficiency for CCGT power plant. It is noticed that, the overall thermal efficiency of the CCGT power plant increases with compression pressure ratio as well as isentropic compressor and turbine efficiency of the gas turbine cycle. yet, the variation of overall thermal efficiency is slight at lower compression ratio and more significant at higher compression pressure ratio for both of the isentropic compressor and turbine efficiency.

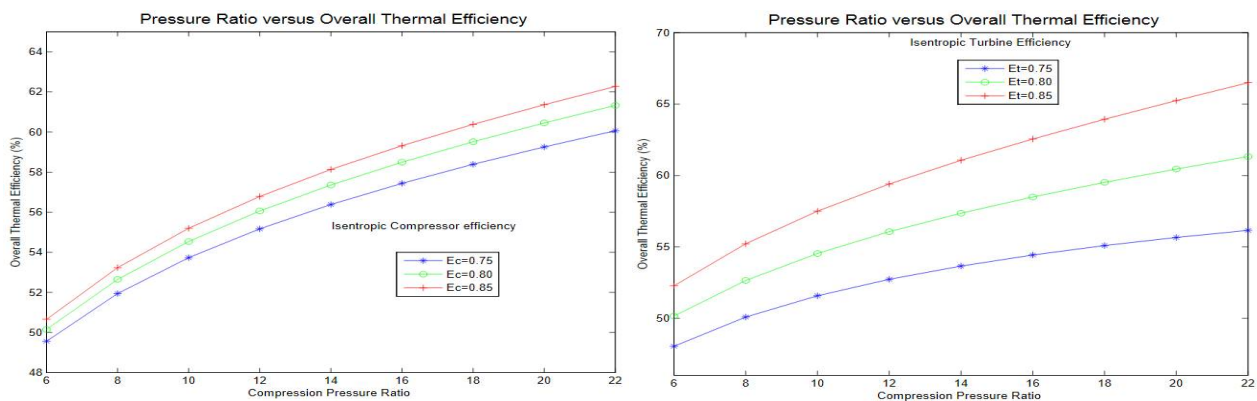


Figure 4. Effect of compression pressure ratio on overall thermal efficiency: a) Isentropic compressor efficiency b) Isentropic turbine efficiency.

The overall thermal efficiency of the CCGT power plant with effect high compression ratio of the gas turbine cycle increases from 60.06% to 62.27% when the isentropic compressor efficiency increases from 75% to 85% as shown in Fig. 4(a), on other hand, when the isentropic turbine efficiency increases from 75% to 85% the thermal efficiency was increased from 56.15 % to 66.49 % as revealed in Fig. 4(b)

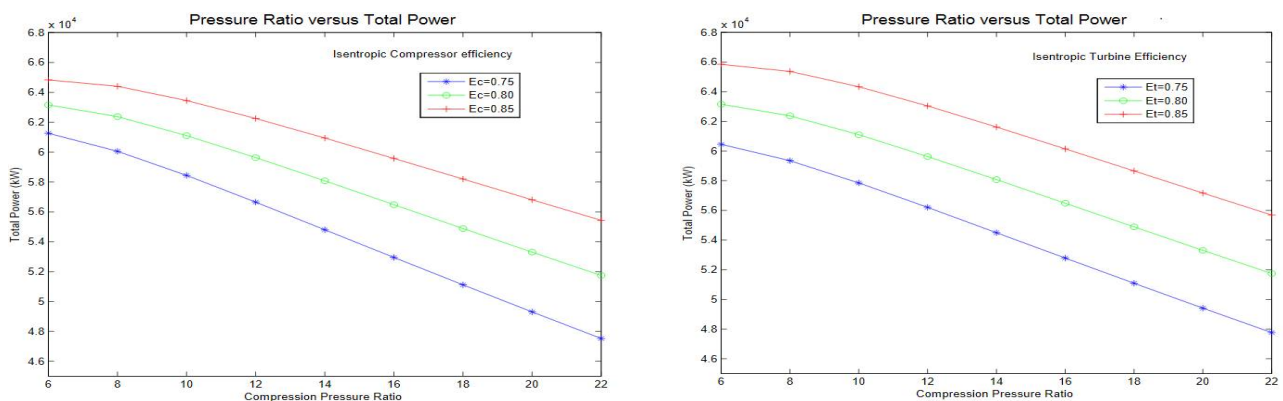


Figure 5. Effect of Compression pressure ratio on Total Power : a) Isentropic compressor efficiency b) Isentropic turbine efficiency.

Figure. 5 shows that increase in the compression ratio and decrease of the isentropic efficiencies of both compressor and turbine of the gas turbine cycle leads to the decrease in the total power output of the CCGT power plant. Moreover, it is observed that at the lower compression pressure ratio there is a small variation in the total power output of CCGT power plant and there is a major variation at the higher compression ratio. Powers outputs of the gas turbine decreases with higher the compression ratio and lowers the isentropic efficiencies of compressor and turbine vice versa.

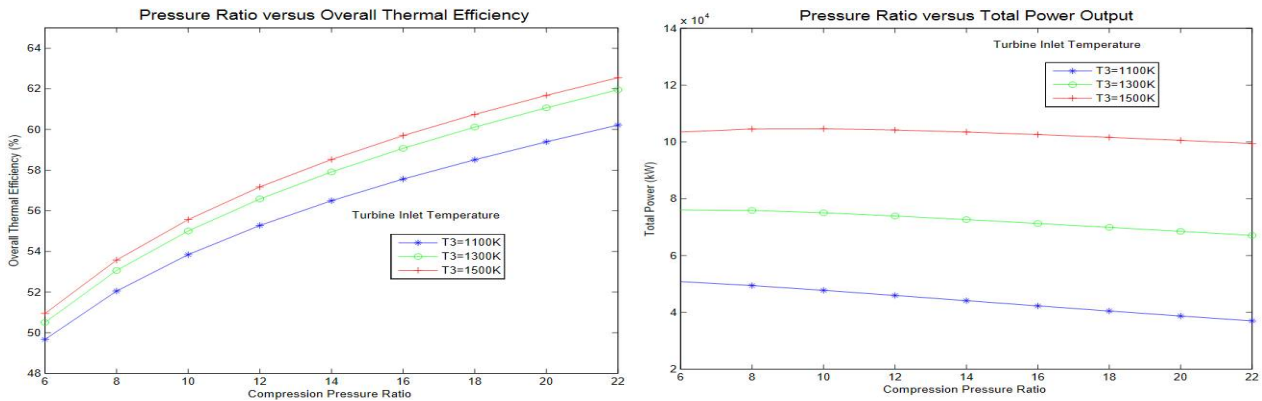


Figure 6. Effect of Compression pressure ratio along with Turbine inlet Temperature Variation on overall thermal efficiency: a) Isentropic compressor efficiency b) Isentropic turbine efficiency.

Fig. 6(a) is observed that the increase in the overall thermal efficiency of the CCGT power plant with increase of the compression ratio at higher turbine inlet temperature.. The overall thermal efficiency at high compression ratio raises from 60.22% to 62.55% with an increase of the turbine inlet temperature from 1100 K to 1500 K. Fig. 6(b).views that increase in the compression ratio and decrease of the turbine inlet temperature of the gas turbine cycle leads to the decrease in the total power output of the CCGT power plant. Moreover, it is observed that at the lower compression pressure ratio, there is a small variation in the total power output of CCGT power plant, while there is a significant variation at the higher compression ratio. Increase in the power output of the gas turbine with the compression ratio to a certain value and thereafter decreases continuously.

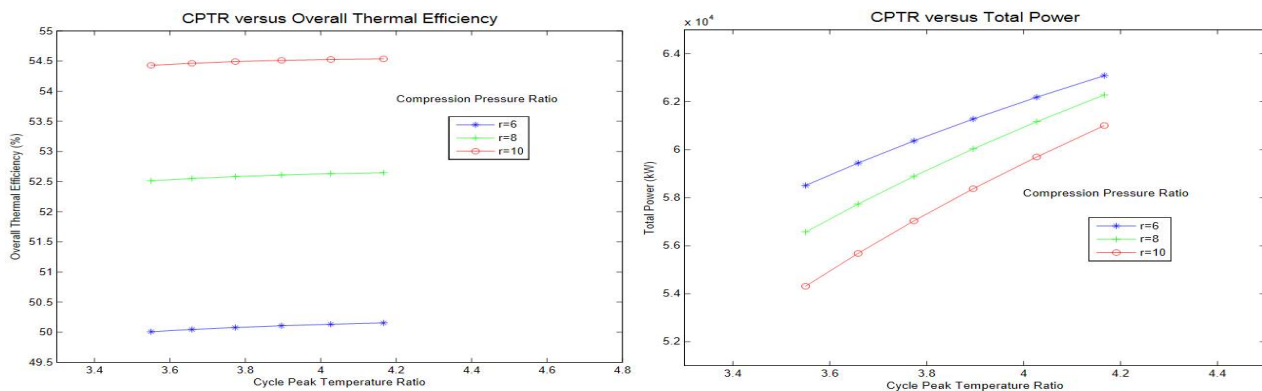


Figure 7. Effect of changing of cycle peak temperature ratio on: a) Overall thermal efficiency b) Total power output with effect of various values of the compression pressure ratio with invariable turbine inlet temperature

Figure 7 views a relation between the cycle peak temperature ratios for varied values of compression ratio versus the overall thermal efficiency and total power outputs. In Fig. 7(a), presents the increases of cycle peak temperature ratio as well as the higher values of compression leads to increases the overall thermal efficiency of CCGT, conversely, the overall thermal efficiency of the CCGT is low at lower cycle peak temperature ratio and lower compression ratio. In Fig. 7(b), shows that the increase in the cycle peak temperature ratio with lower compression ratio, led to increases the total power output. It's due to performance calculations were built with constant turbine inlet temperature causes to increases compressor work with constant work developed by the gas turbine in the CCGT power plant.

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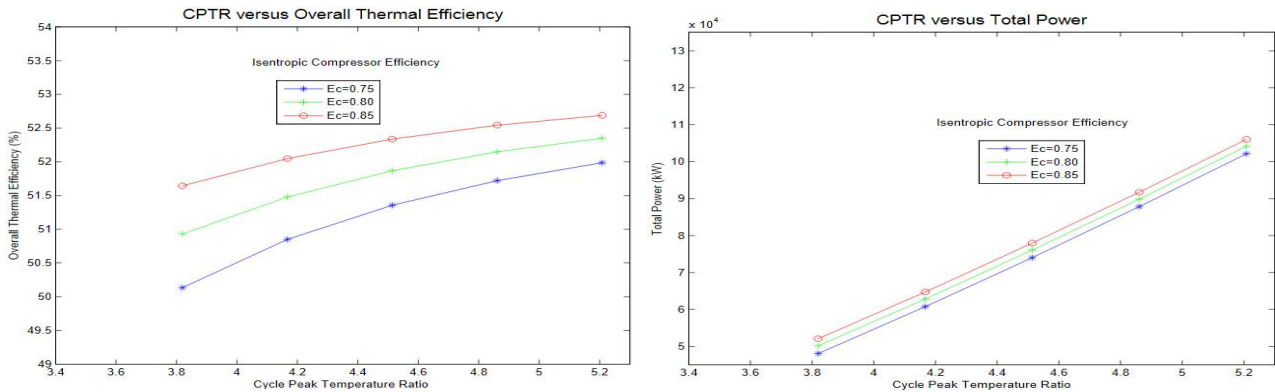


Figure 8. Effect of changing of cycle peak temperature ratio on: a) Overall thermal efficiency b) Total power output, with effect of various values of the isentropic compressor efficiencies with constant ambient temperature.

Figure 8 shows the variation of overall thermal efficiency and total power output of the CCGT power plants with effect of the cycle peak temperature ratio and isentropic compressor efficiency of the gas turbine cycle. Fig. 8 (a) displays that increase in the cycle peak temperature ratio along with increase in isentropic compressor efficiency of the gas turbine cycle leads to increase the overall thermal efficiency, Fig. 8 (b) shows that the increase of the cycle peak temperature ratio along with increase of the isentropic compressor efficiency causes work required to drive the air compressor to reduce leads to increase in the total power output of the CCGT power plant.

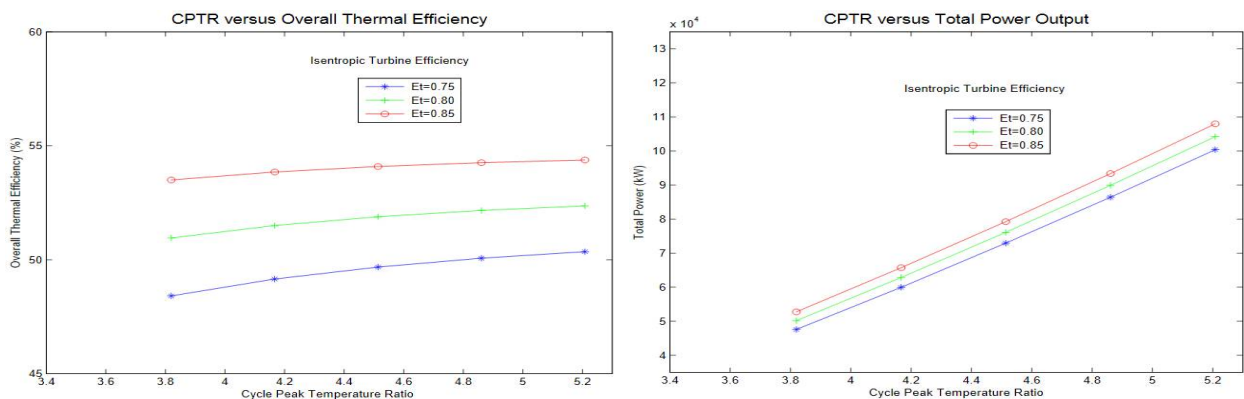


Figure 9. Effect of changing of cycle peak temperature ratio on: a) Overall thermal efficiency b) Total power output, with effect of various values of the isentropic turbine efficiencies with constant ambient temperature.

Figure 9 shows the variation of cycle peak temperature ratio and isentropic turbine efficiency on overall thermal efficiency and total power output of the CCGT power plants. In Fig. 9(a), shows that the overall thermal efficiency with effect of high cycle peak temperature ratio raise from 50.35% to 54.37%, and for low CPTTR overall thermal efficiency varies from 48.41% to 53.50% when the isentropic turbine efficiency increases from 75% to 85%. Fig. 9(b). it can be seen that when the cycle peak temperature ratio increase along with increase in isentropic turbine efficiency of the gas turbine leads to increases the total power output due to increase in work developed by gas turbine at constant compressor work.

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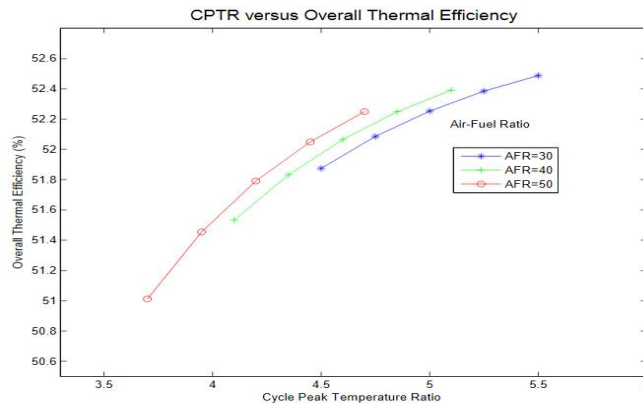


Figure 10. Effect of varying cycle peak temperature ratio and air-fuel ratio on overall thermal efficiency.

Figure 10 shows the impact of cycle peak temperature ratio on the overall thermal efficiency of a CCGT for different values of the air-fuel ratio. It is noticed that, when the cycle peak temperature ratio increases the overall thermal efficiency also increase, but it is decreasing with increase the air fuel ratio. When the air fuel ratio decrease from 50 to 30 the cycle peak temperature ratio varying from 5.5 to 3.7, so the overall efficiency of a CCGT decreases from 52.48% to 51.02%.

V. CONCLUSION

The MATLAB simulation model of the CCGT plant with the varying compression pressure ratio and cycle peak temperature ratio of the gas turbine has been used for carrying out the thermodynamic analysis. The simulated model results are summarized as follows

1. The air to fuel ratio, compression ratio, cycle peak temperature ratio and the isentropic efficiencies of both compressor and turbine are greatly influenced over the overall thermal efficiency of the CCGT.
2. The optimal overall thermal efficiencies of a CCGT compared to the individual thermal efficiencies of a GT cycle and ST cycle power plants.
3. The overall thermal efficiency increases with increasing the cycle peak temperature ratio as well as the compression ratio with stable turbine inlet temperature.
4. The total power output decreases linearly with a decrease of cycle peak temperature ratio along with increase in the compression ratio with constant turbine inlet temperature.

REFERENCES

- 1) Thamir K. Ibrahim, Marwah N. Mohammed "Thermodynamic Evaluation of the Performance of a Combined Cycle Power Plant" International Journal of Energy Science and Engineering Vol. 1, No. 2, 2015, pp. 60-70
- 2) Thamir K. Ibrahim, M.M. Rahman, (2012) "Effect of Compression Ratio on Performance of Combined Cycle Gas Turbine", International Journal of Energy Engineering, Vol. 2, No. 1, pp 9-14.
- 3) Cengel Y. A. and Michael A. Thermodynamics an engineering approach, McGraw-Hill Science/Engineering/Math; 8 edition, 2015.
- 4) Dillip Kumar Mohanty*, Vijay Venkatesh "Performance Analysis Of A Combined Cycle Gas Turbine Under Varying Operating Conditions", Mechanical Engineering: An International Journal (MEIJ), Vol. 1, No. 2, August 2014
- 5) Barinaadaa Thaddeus Lebele-Alawa, Anthony Kpegele Le-ol "Improved Design of a 25 MW Gas Turbine Plant Using Combined Cycle Application" Journal of Power and Energy Engineering, 2015, 3, 1-14
- 6) Dechamps, P. J., Advanced combined cycle alternatives with the latest gas turbines. Transactions of the ASME, Journal of Engineering for Gas Turbines Power, 1998; 120(3): 350-357.
- 7) Chandraa, H., Aroraa, A., Kaushik, S.C., Tripathi, A. and Rai, A., Thermodynamic analysis and parametric study of an intercooled-reheat closed-cycle gas turbine on the basis of a new isentropic exponent. International Journal of Sustainable Energy, 2011; 30(2): 82-97.
- 8) El-Hossani, K.M. and Dorosti, Q. Improvement of gas turbine performance test in combine cycle. World Academy of Science, Engineering and Technology, 2009; 58: 383-386.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Website: www.ijirset.com

Vol. 6, Issue 6, June 2017

- 9) Erdem, H.H. and S.H. Sevilgen. Case study: Effect of ambient temperature on the electricity production and fuel consumption of a simple cycle gas turbine in Turkey. *Applied Thermal Engineering*, 2006; 26(2-3): 320-326.
- 10) R.K.Rajput, *Thermal Engineering Reference Textbook*
- 11) Ahmed, S.Y. (2013) Performance of the Combined Gas Turbine-Steam Cycle for Power Generation. *Mathematical Theory and Modeling*, 3, 12.
- 12) Naradasu R.K., Konijeti R.K., Alluru, V.R. (2007) "Thermodynamic analysis of heat recovery steam generator in combined cycle power plant", *Thermal Science.*, Vol. 11, No. 4, pp. 143-156.
- 13) Thamir, K. Ibrahim, Rahman, M. M., Sharma, K. V., Influence of operation conditions on performance of combined cycle gas turbine, 3rd International Conference on Mechanical and Electrical Technical (ICMET2011) Dalian, China, August 26- 27, 2011; 3, 9-15, ASME Press, Book No.: 859810, ISBN: 978-0-7918-5981-0.