Performance Optimization of Combined Cycle Power Plant Considering Various Operating Parameters

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ABSTRACT

Combined cycle power plants are popular in thermal engineering field for their higher efficiency as compared to normal cycles such as Rankine and Brayton Cycle. But main disadvantages of the cycle are waste heat rejection and low work output. To overcome these difficulties a heat recovery system is used in present work to recover waste heat of Brayton cycle as a steam generator for Rankine cycle in a combined Gas-Vapor cycle. In present work, effect of factors such as "compression ratio", "inlet air temperature" and "turbine inlet temperature" on cycle efficiency was calculated. It was found that cycle efficiency increases with increase in these factors. It was found that optimum value of compression ratio is 12-18 for maximum output of combined cycle. Whereas inlet air temperature has adverse effect on cycle efficiency so it should be kept lower while increase in turbine inlet temperature increases the cycle's work output and hence efficiency. Optimum values of turbine inlet temperature were found in range of 1600-1700 K

Keywords: *Combined cycle efficiency, Work Output, Compression Ratio (12-18), Inlet Air Temperature (IAT), Turbine Inlet Temperature (TIT).*

Nomenclature:-

AP = Approach Point
PP = Pitch Point
T = Temperature

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WHRB = Waste Heat Recovery Boiler
$\dot{Q}$ = Heat Transfer Rate
w_C, w_T = specific work output of compressor and turbine
h = Enthalpy
C_P = Specific heat at constant pressure.
EO = Economizer Outlet.
FW = Water Flow Rate.
ST = Steam
G = Gas
W = Water
TIT = Turbine Inlet Temperature
T_{GEX} = Exit Gas Temperature
r = Compression Ratio
η = Efficiency
η_{CC} = Combined Cycle Efficiency.

Introduction

In electric power generation, a combined cycle is an assembly of heat engines that work in tandem off the same source of heat, converting it into mechanical energy, which in turn usually drives electrical generators. The principle is that the exhaust of one heat engine is used as the heat source for another, thus extracting more useful energy from the heat, increasing the system's overall efficiency. This works because heat engines are only able to use a portion of the energy their fuel generates (usually less than 50%). The remaining heat (e.g., hot exhaust fumes) from combustion is generally wasted. Combining two or more thermodynamic cycle results in improved overall efficiency and reduces fuel costs. In stationary power plants, a successful, common combination is the Brayton cycle (in the form of a turbine burning natural gas or synthesis gas from coal) and the Rankine cycle.

In combined cycle, a gas turbine generator generates electricity and heat in the exhaust is used to make steam, which in turn drives a steam turbine to generate additional electricity. This last step enhances the efficiency of electricity generation. Many new gas power plants in North America and Europe are of this type. Such an arrangement used for marine propulsion is called combined gas (turbine) and steam (turbine) (COGAS). Conversion of an existing steam power plant in a combined cycle power plant is cost effective as well as more efficient as compared to former [1]. Based on recent technology and future demand the main focus in study of CCGT is to focus on exergy optimization by reducing heat loss [2]. Moreover the power production of combined cycle can be increased by evaporator and absorption cooling up to 5-10% whereas as precooling of cycle reduce the temperature range of combustion chamber [3, 4].

Various comparative studies on various kind of combined cycles and methods of improving efficiency of combined cycle and has been done by developing a genetic algorithm to study complex design of combined cycle for utilizing waste heat [5-8]. In 2004, exergy analysis of reheat combined cycle was done to design and optimization of cycle which in turns conclude that the efficiency and power output of the cycle can be increased by replacing reheat in expansion process [9, 10]. Cyclic efficiency of power plant can be increased by using air precooler connected to the evaporator of power plant [11]. Kakaras et al. [12-13] developed three method for air cooling viz; a) evaporative cooling b) refrigeration cooling c) evaporative cooling of pre-compressed air. It was concluded that the highest incremental electricity generation is realized by absorption intake air cooling. In terms of the economic performance of the investment, the evaporation cooler has the lowest cost of incremental electricity generation and lowest payback period. Concerning to the cooling method of pre-compressed air, the results shows a significant gain in capacity, but the total cost of incremental electricity generation in this case is the highest.

The cyclic performance of power plant can be increased by maximizing turbine rotor inlet temperature in the gas turbine; optimizing the gas turbine pressure ratio for gas turbine performance; optimizing steam turbine and boiler pressure; and maximizing steam injection in the gas turbine [14, 15]. Whereas pre-cooling of inlet air by absorption chiller can increase the cycle efficiency [16]. Butcher & Reddy [17] studied performance of a waste heat recovery power generation system based on second law analysis is investigated for various operating conditions. The temperature profiles across the heat recovery steam generator (HRSG), network output, second law efficiency and entropy generation number are simulated for various operating conditions.

Hawaj & Mutairi [18] investigated the effect of different parameters, such as steam to gas mass flow rate ratio, inlet steam turbine temperature, compressor pressure ratio, and gas turbine (GT) combustion efficiency on the performance of the combined cycle. In another aspect of the study, the relative advantage of using CCPP with absorption cooling over thermally equivalent mechanical vapor compression (MVC) cooling was also demonstrated. Whereas reheated cycle is best cycle as compared of single stage cycle and intercooled cycle [19]. Locopo et al. [20] did second law analysis of three different cycles viz., a cycle uses exhaust gases produced by the engine, another with the addition of cooling water with engine exhaust, and third, a regenerated cycle. The overall efficiency of the cycle was increased by 12% for the cycle without bottoming.

Godoya et al. [21] characterized combined cycle gas turbine power plants by minimum specific annual cost values and determined wide ranges of market conditions as given by the relative weights of capital investment and operative costs, employing a non-linear mathematical programming model. Sipheng Zhu et al. [22] did a theoretical study of bottoming the Rankine cycle to recover engine waste heat by comparing five different working fluid on MATLAB software. Engine performance was mainly affected by working fluid properties and superheating temperature which causes slight changes in the overall efficiency of the cycle. Martinez et al. [23] reviewed micro heat and power system with renewable energy resources. Khan et al. [24] use bypass valves to optimize the performance and a 45% increase in network output was obtained with an increase in turbine inlet temperature from 1000K to 1400K simultaneously increasing the efficiency of the cycle from 15% to 31%. More ever the plant efficiency can be increased by providing sequential combustion and steam cooling [25]. Ahmadi et al. [26] reviewed solar power technologies used for electric power generation. Their work points out two ways of generating electricity by solar energy viz; converting solar irradiations into electricity using PV model, and, secondly, harnessing thermal energy by implementation of concentrated solar power (CRS) plants like Linear Fresnel collectors and parabolic trough collectors showing that PV modeled power plants are the better ones as compared to CRS.

A simulation model was proposed by Kumar et al. [27] for determining steam flow rate and overall efficiency of 250 MW coal based power plant. Effect of varying load on thermal efficiency of the plant was discussed and results shows that overall efficiency of the plant was slightly affected with increase in load. In 2019, Kumar et al. [28] proposed two ways of waste heat recovery system of a gas engine to generate electricity. In first approach a single heat recovery boiler was used in which all mixed gases are allowed to pass through before entering to pre-heater and grid cooler. Whereas, in second method, vapor mixture was allowed to pass through steam turbine. Comparing the both methods resulted that the first approach recovered 23931 KJ/s of waste heat with 23.5% power generating efficiency whereas in second approach 21253 KJ/s waste heat was recovered with 22.2% efficiency.

Since last few years various case studies and energy analysis as well as economical aspects of combined cycle power plant has been done [29-31]. In the present study effect of some design parameters such as gas turbine compression ratio, ambient air temperature, turbine inlet temperature, on factors such as fuel consumed (kg) per 100 kg of air, gas turbine outlet temperature, work obtained from the combined cycle, combined cycle efficiency will be calculated.

Design principle

An open circuit gas turbine cycle has a compressor, a combustor, and a turbine. In this type of cycle, the inlet turbine temperature and flue gas temperature are kept in ranges of 900-1400 °C, and, 450 to 650 °C respectively. This range of temperature provides a lot of heat to be used in the Rankine cycle for the generation of steam. In the present work, the turbine's exhaust heat passed through a heat recovery steam generator (HRSG) with a live steam temperature between 420 and 580 °C to convert water into steam. The cooling process in the Rankine cycle is done by circulating water from outside sources like rivers of the cooling tower at low temperature, say, 15 °C.

Working Principle

A combined cycle power plant consists of a Brayton cycle at the first stage and a Rankine Cycle on a later stage is shown in Figure 1. In the first stage air as a fuel is compressed isentropically in an air compressor and then sent to the combustion chamber where compressed air is heated by fuel. The hot gas is then made to flow over turbine blades which in turn generate electricity and the exhaust is passed to the heat recovery steam generator. The output as steam from the steam generator is now used as working fluid for the second stage i.e. in the Rankine cycle, to generate electricity. At the second stage, the steam output from the steam generator is now passed to the steam turbine which in turns generates electricity and the exhaust of the steam turbine is passed to the condenser where it condensed in the form water and again fed to the steam generator with the help of water pump as shown in Figure 1.

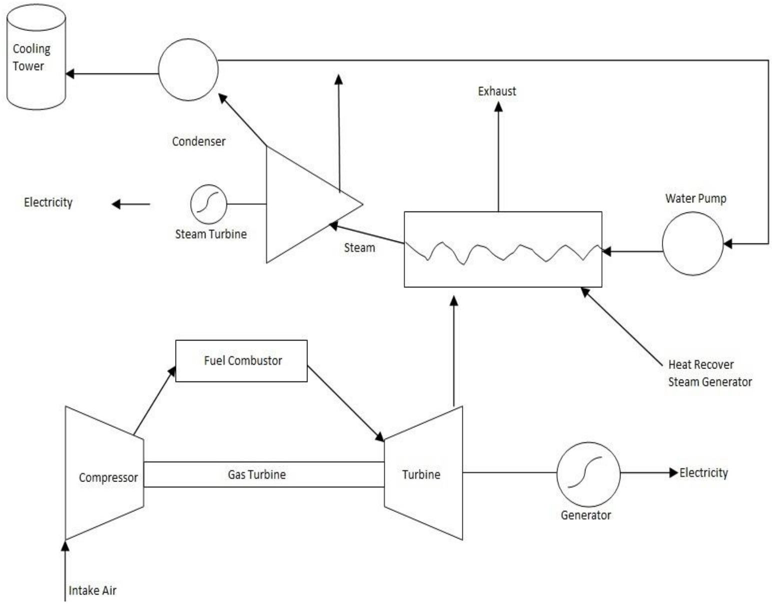

Figure 1: Working principle of single pressure CCPP.

The waste heat recovery process in a single pressure WHRB is illustrated on a temperature profile diagram in Figure 2. Water enters the boiler in the form of compressed liquid at condensate temperature (T_{FW}). As the water receives heat from the hot exhaust gases, it becomes saturated, starts boiling, and is superheated. On the hot side, the exhaust gases leaving the gas turbine enter the steam generator and get cooled finally to the stack temperature (T_{STACK}).

For maximum heat recovery, the stack temperature should approach the acid saturation point of the exhaust gases, while keeping the pressure drop as well as the size of the boiler within the desirable limits. The factors which affect the cost and effectiveness of any WHRB are the pinch point, approach point, allowable backpressure, stack temperature, steam pressure, and steam temperature. The minimum temperature difference for heat transfer, which is known as pinch point plays an important role in identifying the optimum heat recovery and size of heat exchangers. The approach point is the difference between the saturation temperature and the temperature of water leaving the economizer. Lowering the approach point will increase the probability of steaming in economizer which may cause hammering and blanketing.

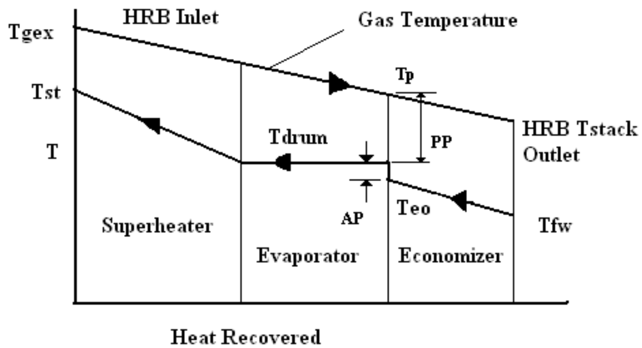

Figure 2: Temperature/Heat energy diagram for a single pressure WHRB.

The gas side pinch point temperature (T_P) and economizer exit temperature (T_{EO}) are calculated by assuming the drum saturation pressure (P_{Drum}).

$$T_P = T_{DRUM} + PP \tag{1}$$

$$T_{EO} = T_{DRUM} - AP \tag{2}$$

The steam generated for each kg/sec of exhaust gases can be determined by applying mass and energy conservation principles across the super-heater and evaporator.

$$\dot{m} = \dot{m}_{GEX} \times C_{PG} \frac{(T_{GEX} - T_P)}{(h_{ST} - h_{EO})} \tag{3}$$

The WHRB, being considered is a non-firing boiler. Therefore the heat transfer is predominantly by convection. It is customary to neglect the radiative heat transfer, particularly because the reduction in heat transfer due to soot deposition/ fouling etc. is also ignored and it is assumed that these two approximately compensate each other. The heat across each section of the boiler can be estimated as follow:

$$\dot{Q}_{ECON} = \dot{m}_w(h_{EO} - h_{FW}) \tag{4}$$

$$\dot{Q}_{EVAP} = \dot{m}_w(h_{FG} + C_{PW}(T_{DRUM} - T_o)) \tag{5}$$

$$\dot{Q}_{SUPR} = \dot{m}_w(h_{ST} - h_{FG}) \tag{6}$$

The flue gas temperature in the stack can also be estimated based on the heat balance across economizer.

$$T_{STACK} = T_P - \dot{m}_w \times \frac{(h_{LPEO} - h_{FW})}{(\dot{m}_{GEX} \times C_{PG})} \tag{7}$$

Low stack temperature is always desirable from the point of waste recovery. However, to avoid the corrosion from moisture formation in the economizer, the minimum temperature should always be kept higher than the acid dew point temperature. Also, the size of the economizer depends on the stack temperature which has, therefore, to be justified on the economic consideration.

Mathematical Modeling

The following Parameters are taken for the present study:

Compression ratio:	8-20
Inlet Air Temperature:	275-325 K
Turbine Inlet Temperature	1250-1700 K

The effect of all these parameters was studied to establish the combined cycle work output and efficiency. For a given compressor isentropic efficiency

η_c and pressure ratio r_c, other state variables for the incoming and outgoing streams can be calculated. The inlet and outlet humidity ratios will be the same. The energy balance yields the compressor work w_c and compressor outlet temperature.

$$w_{ai} = w_{ao} \tag{8}$$

$$\frac{T_{ao}}{T_{ai}} = [r_c]^{\frac{\gamma_c - 1}{\gamma_c \eta_c}} \tag{9}$$

The polytropic efficiency of the compressor and turbine can be calculated according to:

$$\eta_c = 1 - [0.04 + (r_c - 1)/150] \tag{10}$$

$$\eta_t = 1 - [0.03 + (r_t - 1)/180] \tag{11}$$

$$w_c = (h_{ao} - h_{ai}) \tag{12}$$

Specific heat ratio for the humidified air is being given by the following relation:

$$\gamma_c = \frac{C_{pc}}{C_{vc}} \tag{13}$$

where C_{pc} and C_{vc} can be determined from the following relations:

$$C_{pc} = C_{pa} + w_{ai} C_{pw} \tag{14}$$

$$C_{vc} = C_{va} + w_{ai} C_{vw} \tag{15}$$

Specific heat of air at constant pressure is given by the following relation:

$$C_{pa} = C_0 + C_1 T + C_2 T^2 + C_3 T^3 + C_4 T^4 \tag{16}$$

$$C_{va} = C_{pa} - R \tag{17}$$

$$C_p = C_{pa} + \frac{f}{f+1} \theta_{cp} \tag{18}$$

where,

$$\theta_{cp} = CP_0 + CP_1T + CP_2T^2 + CP_3T^3 + CP_4T^4 + CP_5T^5 \tag{19}$$

Enthalpy of air is being given by the following formula:

$$h_a = \int_0^T C_{pa} dt \tag{20}$$

$$h_a = C_0T + \frac{C_1}{2}T^2 + \frac{C_2}{3}T^3 + \frac{C_3}{4}T^4 + \frac{C_4}{5}T^5 + CH \tag{21}$$

For the expansion ratio of the gas turbine, "r_e" temperature at the exit of the turbine isentropic process can be calculated by:

$$T_{gos} = T_{gi}(r_e)^{\frac{(\gamma_g - 1)}{\gamma_g}} \tag{22}$$

The actual temperature T_{go} at the exit of the turbine can be calculated by:

$$\eta_T = \frac{T_{gi} - T_{go}}{T_{gi} - T_{gos}} \tag{23}$$

The energy balance yields the turbine work w_T given by the following relation:

$$w_T = (h_{gi} - h_{go}) \tag{24}$$

Change in enthalpy of air after adding fuel in the combustion chamber is:

$$\eta_{cc} m_f CV = h_{go} - h_{gi} = h_3 - h_2 \tag{25}$$

where h_{go} may be calculated as:

$$h_{go} = h_a + \frac{f}{1+f}\theta_h \tag{26}$$

$$\theta_h = H_0 + H_1T + H_2T^2 + H_3T^3 + H_4T^4 + H_5T^5 \tag{27}$$

Heat transfer and efficiency can be calculated by the following equations:

Pump work:

$$w_P = V_f(P_{DRUM} - P_{COND}) \tag{28}$$

If the efficiency of the pump is taken into consideration then:

$$h_{FW} = h_f + \frac{h_{FW} - h_f}{\eta_p} \tag{29}$$

Work done by the steam turbine is:

$$(W.D)_{ST} = h_{MST} - h_{EX} \tag{30}$$

Net work done will be:

$$(W.D)_{net} = (W.D)_{ST} - W_p \tag{31}$$

$$\dot{Q}_{SC} = (h_{MST} - h_{FW}) \tag{32}$$

Hence the associated bottoming cycle and plant efficiencies are:

$$\eta_{SC} = \frac{(W.D)_{net}}{Q_{SC}}$$

$$\eta_{CC} = \frac{P_{GT} + P_{SC}}{Q_{in}} = \frac{P_{CC}}{M_f LHV} \tag{33}$$

Result Analysis and Discussion

For the present study, the pressure ratio of gas turbines varied from 8 to 20 bar. With an increase in compression ratio, compressor exit temperature increases which result in the decrement of fuel consumption keeping the inlet temperature of the turbine constant (Figure 3). In the present work capacity of the blade material of the turbine for bearing thermal stress was kept on mind for deciding values of the inlet gas temperature of the turbine. The main purpose of the study is to focus on the recovery of waste heat of gas turbine exit which can be utilized to generate steam in steam turbines and further generate electric power by implementing heat recovery steam generator.

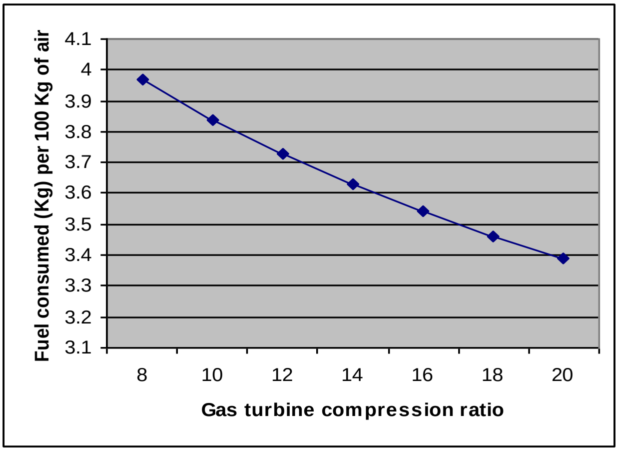

Figure 3: Effect of gas turbine compression ratio on fuel consumption

The cycle compression ratio has a direct effect on gas turbine outlet temperature. As the compression ratio increases, gas turbine outlet temperature decreases which makes lesser heat available for pressurized water in HRSG (Figure 4).

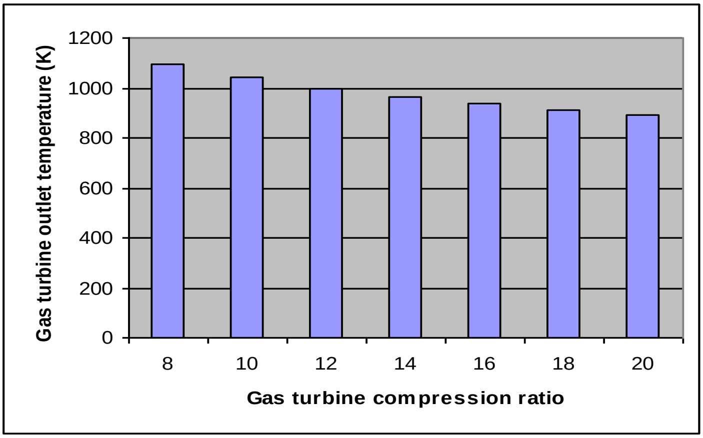

Figure 4: Effect of the compression ratio of the gas turbine on gas turbine outlet temperature.

For the lower cycle pressure ratio, sufficient heat is available to convert the pressurized water into steam. But after a pressure ratio of 18, flue gas temperatures becomes low enough to lower the heat supplied to pressurized water. Due to this steam turbine work output is decreased and after the pressure ratio of 18, a decreased work output from the cycle is obtained (Figure 5).

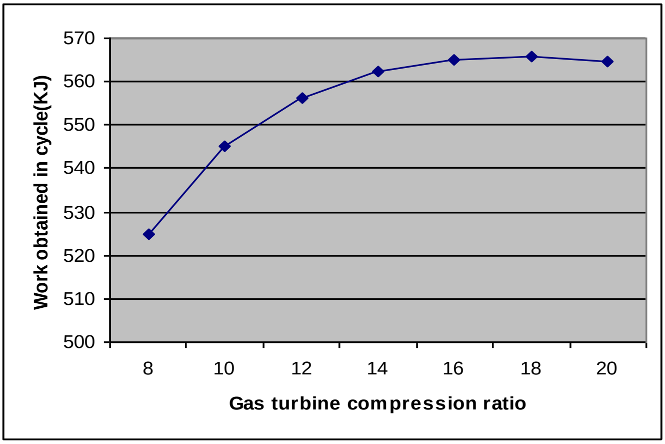

Figure 5: Change in work obtained from a combined cycle with a change in gas turbine compression ratio.

As it may be observed that there is not much gain in work output by changing the compression ratio but efficiency gain is reasonable (Figure 6). To calculate the cycle efficiency a ratio of work output and energy supplied is taken. As the increase in pressure ratio lower the fuel consumption so the energy supplied to the cycle decreases and efficiency increases.

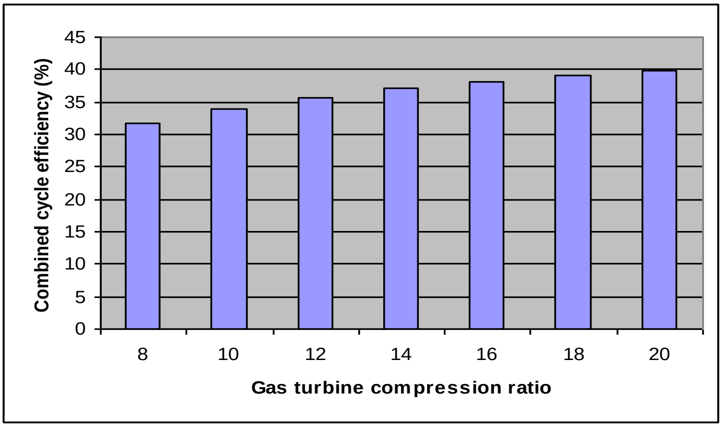

Figure 6: Change in combined cycle efficiency with a change in gas turbine compression ratio.

Ambient air temperature never remains constant. Now from the analysis, it is being found that as the IAT will increase fuel requirement will decrease. This is because TIT is fixed for this case and if the IAT increases then the combustion chamber inlet temperature will also increase. But the combustion chamber outlet temperature is fixed. So the fuel requirement decreases (Figure 7).

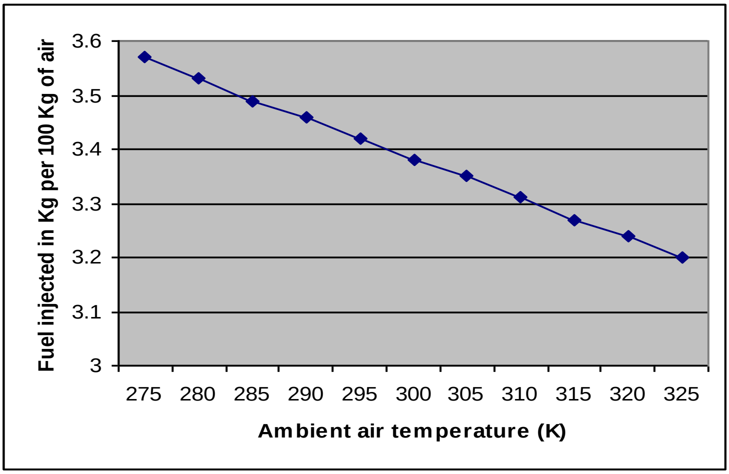

Figure 7: Change in fuel injected in the combustion chamber with a change in ambient air temperature.

For the design conditions if the TIT is fixed then, as the gas turbine inlet temperature will keep on increasing then the fuel requirement will decrease. But due to the increase in the ambient temperature the mass flow rate of the air to the compressor also decreases which leads to lesser work output and lesser efficiency (Figure 8). Inlet air cooling may bring the ambient air to the designed condition.

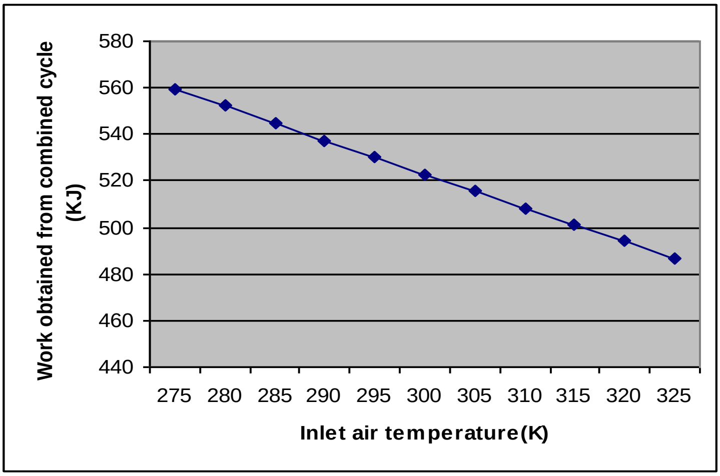

Figure 8: Change in work obtained from a combined cycle with a change in inlet air temperature.

An increase in ambient temperature reduced fuel consumption and simultaneously work output also decreased to a level that has a considerable impact on the performance of the combined cycle causing lower efficiency as shown in Figure 9. With the increase in the inlet or ambient air temperature, the fuel requirement of the combined cycle decreases by 11%, and similarly work output of the cycle also decreases by 14% which has more impact on cycle efficiency, thus, causing a reduction in combined cycle efficiency (Figure 9).

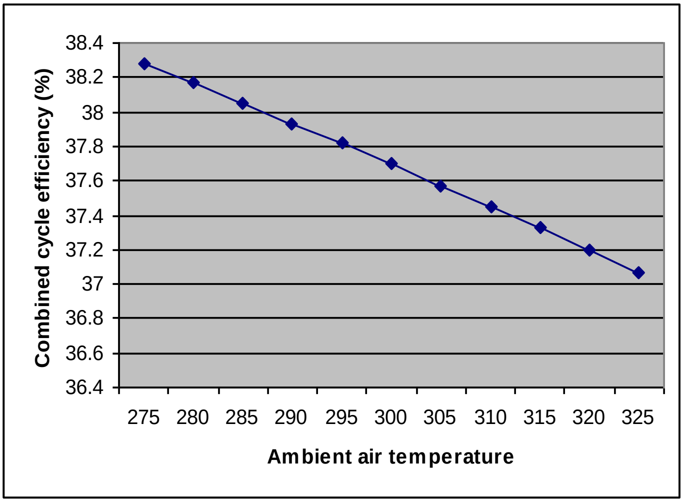

Figure 9: Change in combined cycle efficiency with a change in ambient air temperature.

Highest TIT is decided by the metallurgical stress-bearing capacity of turbine blade material. With the higher TIT larger is the fuel consumption and work obtained in the cycle and combined cycle efficiency also increases. For designing the gas turbine the compression ratio is kept between the maximum work and maximum efficiency. Increasing the TIT increases combined cycle efficiency. Benefit of increasing a lower temperature is more and it decreases with TIT. It is so due to increase in the consumption of fuel to attain higher TIT. After a turbine inlet temperature of 1700 K not much increase in efficiency is observed.

A significant increase in combined cyclic efficiency was noted with a varying inlet temperature of flue gases in the turbine. Higher flue gas temperature at turbine inlet results in larger work output and hence the performance increases as well. But as the inlet temperature of flue gases reaches a value 1700K no further significant change in combined cycle performance was achieved.

The energy analysis is not sufficient for accurate prediction of combined cycle power plant performance. Energy analysis gives only an idea about the efficiency and work obtained from the cycle. It does not tell us about the major sites of energy losses. For the complete analysis exergy analysis is also required. The present work makes a base for the exergy analysis.

Conclusion

In present work, waste heat of gas turbine was used to generate electricity by implementing heat recovery steam generator. Fuel consumption of power plant can be reduced by increasing compression ratio keeping inlet temperature of gas turbine constant, which in turn, decreases the gas turbine outlet temperature resulting less available heat for steam generator. With increase in compressor ratio, the cycle's work output and efficiency increases significantly and reaches to a maximum value at compression ratio 18 bar. It was observed that an increase in pressure ratio lower the fuel consumption and thus less energy consumption was occurred thus increased cyclic efficiency was obtained. Inlet ambient air temperature has adverse effect on cycle's efficiency and should be kept below 270 K. Turbine inlet temperature has remarkable effect on cycle's efficiency. It was observed that when turbine inlet temperature reaches to 1500 K then cycle's efficiency and work output increases effectively and from results it is clear that cycle reaches to maximum efficiency at 1700 K.

References

[1] Y. S. H. Najjar & M. Akyurt, "Combined cycle with gas turbine engine", *Heat Recovery Systems & CHP,* vol 14, no. 2, pp 93-103, 1994.

[2] J.H. Horlock, "Combined power plants present, and future", *Joumal of Engineering for Gas Turbines and Power, vol.* 117, pp 608-616,1995.

[3] M. De Lucia, C. Lanfranchi, & V. Boggio, "Benefits of compressor inlet air cooling for gas turbine cogeneration plants", *ASME Journal for Gas Turbine and Power,* vol. 118, pp 598-603, 1996.

[4] M. Mostafavi, A. Alaktiwi & B. Agnew, "Thermodynamic analysis of combined open-cycle-twin-shaft gas turbine (Brayton cycle) and exhaust gas operated absorption refrigeration unit", *Applied Thermal Engineering,* vol. 18, pp 847-856, 1998.

[5] T. Heppenstall, "Advanced gas turbine cycles for power generation: a critical review", *Applied Thermal Engineering,* vol. 18, pp 837-846, 1998.

[6] P.A. Pilavachi, "Power generation with gas turbine systems and combined heat and power", *Applied Thermal Engineering,* vol. 20, pp 1421-1429, 2000.

[7] Yousef S. H. Najjar, "Effcient use of energy by utilizing gas turbine combined systems," *Applied Thermal Engineering,* vol. 21, no. 4, pp 407-438, 2001.

[8] Manuel Valdés, M Dolores Durán nd Antonio Rovira, " Thermoeconomic optimization of combined cycle gas turbine power plants using genetic algorithms", *Applied Thermal Engineering,* vol. 23, no. 17, pp 2169-2182, 2003.

[9] A. Khaliq & S.C. Kaushik, "Second-law based thermodynamic analysis of Brayton/Rankine combined power cycle with reheat", *Applied Energy,* vol. 78, pp 79–197, 2004.

[10] A. Khaliq & S.C. Kaushik, "Thermodynamic performance evaluation of combustion gas turbine cogeneration system with reheat", *Applied Thermal Engineering,* vol. 24, pp 1785–1795, 2004.

[11] Y.S.Najjar, "Augmentation of gas turbine performance using air coolers", *Applied Thermal Engineering,* vol. 24, pp 415-429, 2004.

[12] E.Kakaras,"Compressor intake air cooling in gas turbine plants", *International Energy Journal,* vol. 29, pp 12-15, 2004.

[13] E.Kakaras, A. Doukelis, A. Prelipceanu, S. Karellas, "Inlet air cooling methods for gas turbine based power plants" - *ASME Journal for Gas Turbine and Power,* vol. 128, pp 312-317, 2006.

[14] T. Korakianitis, J. Grantstrom, P. Wassingho & Aristide F. Massardo, "Parametric performance of combined- cogeneration power plants with various power and efficiency enhancement", *Journal of Engineering for Gas Turbine and Power,* vol. 127, pp 65-72, 2005

[15] Kousuke Nishida, Toshimi Takagi & Shinichi Kinoshita, "Regenerative steam-injection gas-turbine systems", *Applied Energy,* vol. 81, pp 231–246, 2005.

[16] S. Boonnasa, P. Namprakai & T. Muangnapoh, "Performance improvement of the combined power cycle power plant by intake air cooling using an absorption chiller" – *Energy,* vol. *31,* pp 2036-2046, 2006.

[17] C.J. Butcher & B.V. Reddy, "Second law analysis of a waste heat recovery based power generation system", *International Journal of Heat and Mass Transfer,* vol. 50, pp 2355–2363, 2007.

[18] Osamah M. AL-Hawaja & Hamad AL-Mutairi, "A combined power cycle with absorption air conditioning", *Energy,* vol. 32, pp 971–982, 2007.

[19] A.L.Polyzakis, C.Koroneos & G.Xydis, "Optimum gas turbine cycle power plant", *Energy Conversion and Management,* vol. 49, pp 551-563, 2008.

[20] Iacopo Vaja, Agostino Gambarotta, "Internal Combustion Engine (ICE) bottoming with organic Rankine cycles (ORCs)," *Energy,* vol. 35, pp 1084-1093, 2010.

[21] E. Godoy, S.J. Benz and N.J. Scenna, "A strategy for the economic optimization of combined cycle gas turbine power plant by taking advantage of useful thermodynamic relationships", *Applied Thermal Engineering,* vol. 31, no. 5, pp 852-871, 2011,

[22] Sipeng Zhu, Kangyao Deng, Shuan Qu, "Energy and exergy analyses of a bottoming Rankine cycle for engine exhaust heat recovery," *Energy,* vol. 58, pp. 448-457, 2013.

[23] S.Martinez, G.Michaux, P. Salagnac, J.L. Bouvier, "Micro-combined

heat and power systems (micro-CHP) based on renewable energy sources", *Energy Convers. Manag*, vol. 154, pp 262-285, 2017.

[24] M.N. Khan , I.Tilili, " New advancement of high performance for a combined cycle power plant: Thermodynamic analysis", *Case Stusy in Thermal Engineering*, vol. 12, pp 166-175, 2018.

[25] J. Kotowicz, M. Brzeczek "Comprehensive multivariable analysis of the possibility of an increase in the electrical efficiency of a modern combined cycle power plant with and without a CO_2 capture and compression installations study", *Energy,* vol. 175, pp 1100–1120, 2019.

[26] Mohammad Hossein Ahmadi, Mahyar Ghazvini, Milad Sadeghzadeh, Mohammad Alhuyi Nazari, Ravinder Kumar, Abbas Naeimi, Tingzhen Ming, "*Solar power technology for electricity generation: A critical review*", Energy Sci Eng., vol. 6, pp 1–22, 2018.

[27] Ravinder Kumar, Ravindra Jilte, Mohammad H. Ahmadi, Rajneesh Kaushal, "A simulation model for thermal performance prediction of a coal-fired power plant", *International Journal of Low-Carbon Technologies*, vol. 14, pp 1–13, 2019.

[28] Abbas Naeimi, Mokhtar Bidi, Mohammad Hossein Ahmadi, Ravinder Kumar, Milad Sadeghzadeh, Mohammad Alhuyi Nazari, "Design and exergy analysis of waste heat recovery system and gas engine for power generation in Tehran cement factory", *Thermal Science and Engineering Progress*, vol. 9, pp 299–307, 2019.

[29] A. Boretti, S. Al-Zubaidy, "A case study on combined cycle power plant integrated with solar energy in Trinidad and Tobago", *Sustain. Energy Technol. Assess*, vol. 32, pp 100–110, 2019.

[30] A. Kumar, K.C. Nikam, A.K.Bahura, "An Exergy analysis of a 250MW Thermal Power Plant", *Renewable energy Research and Applications*, vol. 1 pp 197-204, 2020.

[31] D. Mugabe, L. Elbakidze, and G. Zaynutdinova, "Elasticity of substitution and technical efficiency: evidence from the US electricity generation," *Applied Economics*, vol. 52, pp. 1789–1805, 2020.