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Influence of Steam Injection on the Performance of Combined Cycle Power Plant

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Abstract: Combined cycle gas turbines are becoming popular to product power at higher efficiencies with reduced pollutants and greenhouse gas emissions. In the present research, the effect of steam injection inside gas turbine combustion chamber and isentropic component efficiencies on the performance of combined cycle gas turbine is investigated. For a particular combined cycle gas turbine configuration, the effect of steam injection in the gas turbine combustor on the performance of gas turbine cycle, steam turbine cycle and fuel consumption is investigated based on 1st law of thermodynamics. Also for a particular combined cycle configuration, the effect of component efficiencies of gas turbine, compressors and the steam turbine on the combined cycle efficiency and the net power output is also conducted. The effect of operation conditions specially the pressure ratio for the gas turbine cycle and the turbine inlet temperature on the performance of combined cycle and gas turbine cycle are investigate and discuss. The result shown the power output increases about 21% with increases the pressure ratio from 5-35 and increases the fraction of steam injection from 0-10%.

Key words: Combined cycle, steam injection, gas turbine, performance, components efficiency, Iraq

INTRODUCTION

In the last four decades, intensive efforts have been made on different components of the combined cycle to improve its performance. One of the most common applications is the gas-steam combined cycle which is composed of a gas turbine cycle (Brayton cycle) and a steam turbine cycle (Rankin cycle) coupled through a Heat Recovery Steam Generator (HRSG) (Tiwari *et al*., 2010). The air is draw from the ambient and compressed to the higher pressure based on the compressor pressure ratio. The compressed air is sent to a combustion chamber where the fuel is mixed with air then burned combustion products are expanded through the turbine to produce power. The exhaust gas from the gas turbine passes through the heat recovery steam generator where steam is generated by extracting waste heat from the gases as shown in Fig. 1. The high pressure and temperature steam generated in the heat recovery steam generator expands through a steam turbine that drives an electric generator and the low pressure steam condenses in a condenser. The pump is used to raise the pressure of working fluid from the condenser pressure to boiler pressure. Currently, a large combined cycle can achieve high efficiencies between 50-60% (Kaushika *et al*., 2011). This efficiency is achieved with a high gas Turbine Inlet Temperature (TIT), up to 1500-1800 K which leads to increasing the exhaust gas turbine temperature. As a result, more steam is generated in the heat recovery steam generator with optimum pressure ratio (Yadav, 2003; Deeharnps, 1998). It has been recognized that there are ways to improve the efficiency of the combined cycle power generation systems by improving the performance of gas turbine an steam cycles. Steam can be injected in the topping cycle at different locations such as before of the combustor through the fuel nozzles premixed with the natural gas, ahead of the lower-pressure turbine and ahead of the power turbine (Poullikkas, 2005). The combined cycles have demonstrated high efficiency and power generation and low installation and operation costs in sizes >50 MW

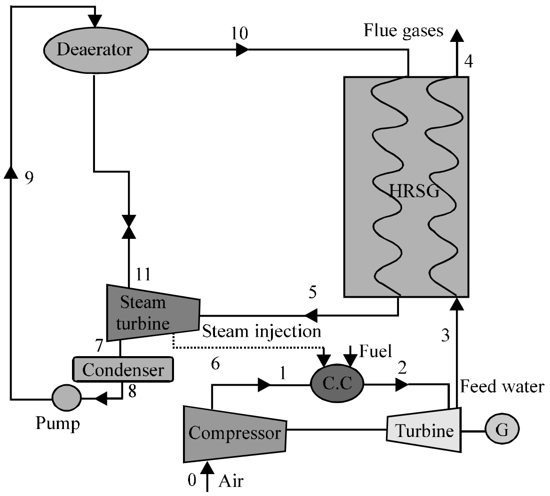

Fig. 1: The schematic diagram of combined cycle gas turbine power plant

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in small gas turbine plants <50 MW, the steam turbine shows an increase of the capital cost. Therefore, the Chong cycle (STIG) with small gas turbine, <50 MW became an attractive technology. Recently, steam injection is being applied in medium and large size gas turbines ranging from 50-125 MW. Many studies have concluded that injected steam has significant impact on the gas turbines' performance, efficiency increases of upto 10% and the power augmentation between 50-70% (Pinelli and Bucci, 2009). The stem injection can improve both thermal efficiency and power generation of gas turbine units (ST1G). There are >100 gas turbine units with steam injection technology based on Cheng cycle are in operation worldwide (Mitre *et al*., 2005). The study by Poullikkas (2005) described the MAST technologies (Mixing Air Steam Technologies) as a promising method to improve the small as turbine's performance (<50 MW). The advantages of this technology such as reducing (N0x) formation in the combustion chamber and using the steam instead of compressed air to cool the gas turbine blades' temperature are described.

The aim of the present research is to investigate the effect of steam injection and role of component efficiencies on the performance of a combined cycle power generation unit. A simulation program based on Matalab has been developed for this purpose.

MATERIALS AND METHODS

Evaluation of the cycle performance parameters: In order to make the gas turbine insensitive with the variation in the ambient temperature, the steam water injection method before the combustion chamber has been proposed. This operation will be carried only when the inlet parameters of compressor exceed the standards conditions values of gas turbine. The calculation of new processes is obtained from an energy balance applied to an elementary volume of the combustion chamber shown in Fig. 2:

$$\dot{m}_a \times h_1 + \dot{m}_f \times LHV + \dot{m}_s \times h_{1s} = \left(\dot{m}_a + \dot{m}_f\right) \times h_{2g} + \dot{m}_s \times h_{2s} \tag{1}$$

and:

$$f = \frac{\dot{m}_f}{\dot{m}_a};\ s = \frac{\dot{m}_s}{\dot{m}_a} \tag{2}$$

Where:

f = Fuel air ratio

s = Fraction of steam injection to compressed air

However to maintain the manufactory combustor at constant temperature with the presence of steam (which the parameters of injection are Tinj and Pinj), the fuel must be added even more. This quantity of the fuel is given by Kadi *et al*. (2007):

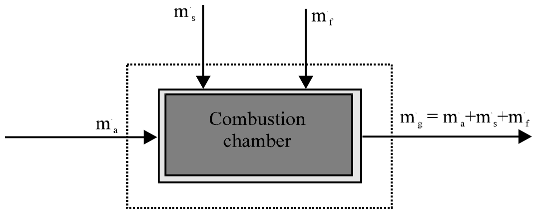

Fig. 2: Control volume of combustion chamber (Application of mass balance)

$$f' = \frac{\left(h_2 - h_1\right) + s \times \left(h_{2s} - h_{1s}\right)}{\eta_{comb} \times LHV - h_{2g}} \tag{3}$$

Where:

h = Enthalpy

LHV = Low Heating Value

η_{comb} = Combustion efficiency

Thus, the fraction steam injection is given by Eq. 4 (Bouam *et al*., 2008):

$$s = \frac{(A - C) \times \alpha + (B - C) \times \sigma}{\sigma \times D - (A - C) \times \beta} \tag{4}$$

Where:

$\alpha = h_{2g} - h_1$

$\sigma = \eta_{comb} \times LHV - h_{2g}$

$\beta = h_{2s} - h_{1s}$

$A = (\eta_{th} \times LHV)/\eta_m$

$B = w/\eta_m$

$C = h_{2g} - h_{3g}$

$D = h_{2s} - h_{3s}$

As the vapor rate is very small comparing with the rate of air, pressure increase in the combustion chamber has been neglected while the steam is injected. The compressor of the engine determines the pressure in the combustion chamber. The exhaust gases temperature from gas turbine is given by Eq. 5 (Naradasu *et al*., 2007):

$$T_3 = T_2\left(1 - \eta_t \times \left(1 - \frac{1}{r_p^{\frac{\gamma_g - 1}{\gamma_g}}}\right)\right) \tag{5}$$

The research generated by the turbine per unit mass of air after receiving combustion gas of mass (1+f) can be written as:

$$W_t = C_{pg} \times \left(T_2 - T_3\right) \tag{6}$$

The net work of the gas turbine (W_{net}) is calculated from the Eq. 6 (Saravanamuttoo *et al*., 2009):

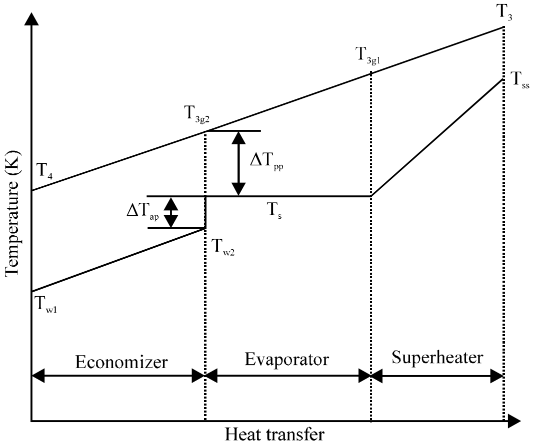

Fig. 3: Schematic of heat recovery zones

$$W_{net} = c_{pg} \times T_2 \times \eta_t \left(1 - \frac{1}{r_p^{\frac{\gamma_g - 1}{\gamma_g}}} \right) - c_{pa} T_0 \left(\frac{r_p^{\frac{\gamma_a - 1}{\gamma_a}}}{\eta_c} \right) \quad (7)$$

The power developed by the turbine is given by:

$$P_{gt} = \left(\dot{m}_a + \dot{m}_f\right) \times \left(h_{2g} - h_{3g}\right) + \dot{m}_s \times \left(h_{2s} - h_{3s}\right) \quad (8)$$

The heat supplied is also expressed as:

$$Q_{add} = \dot{m}_f \times LHV \quad (9)$$

The gas turbine efficiency (η_{th}) can be determining by Eq. 16 (Rahman *et al*., 2011):

$$\eta_{th} = \frac{W_{net}}{Q_{add}} \quad (10)$$

The gas turbine cycle couples with the steam cycle through a heat exchanger which known as a Heat Recovery Steam Generator (HRSG) as shown in Fig. 3. The amount of steam generated in the HRSG is calculated from an energy balance around the superheated and evaporator parts of the HRSG, considering 1% losses as given in Eq. 10. The selection of Pinch Point (TPP) and Approach Temperature (TAP) is the 1st step to determine the gas and steam profile taking into account that the minimum gas mixture temperature at (HRSG) exit is 127°C. Thus, the temperature of exhaust gases at the economizer inlet of the HRSG component is determined in a similar manner to that given in Eq. 5:

$$T_{3g2} = T_s + T_{PP}$$

$$\dot{m}_{st} \times \left(h_5 - h_{w2}\right) + bd \times \left(h_s - h_{w2}\right) = 0.99 \times \dot{m}_g \times \left(h_3 - h_{3g2}\right) \quad (11)$$

Where:

h_s = The saturated enthalpy of the working fluid of bottoming cycle

h_{w2} = Sub-cooled enthalpy of the working fluid of the bottoming cycle

The combined cycle performances can be estimated based on enthalpies of steam, air and the mass flow rates at inlet and outlet of each device in the combined cycle-injected steam. The steam turbine producing power is calculated as:

$$W_{st} = \dot{m}_s \times \left(h_5 - h_6\right) + (\dot{m}_s - \dot{m}_{sl}) \times \left(h_6 - h_{11}\right) + (\dot{m}_s - \dot{m}_{sl} - \dot{m}_{ex}) \times \left(h_{11} - h_7\right) \quad (12)$$

The work consumption by the pump is calculated:

$$W_p = \left(\dot{m}_s - \dot{m}_{sl}\right) \times \left(h_8 - h_9\right) \quad (13)$$

The heat input to the bottoming cycle from HRSG is calculated as:

$$Q_{add,\ bot.} = \dot{m}_g \times \left(h_3 - h_4\right) \quad (14)$$

The performance of combined cycle-steam injection including the thermal efficiencies for topping cycle, bottoming cycle and overall efficiency are calculated, respectively:

$$\eta_{st} = \frac{W_{st} - W_p}{Q_{add,\ bot.}} \quad (15)$$

$$\eta_{overall} = \frac{W_{net} - W_{st} + W_p}{Q_{add}} \quad (16)$$

RESULTS AND DISCUSSION

The performance analysis of the combined cycle integrated with steam injection is investigated considering realistic conditions such as temperature and pressure for each component in a combined cycle unit. The air conditions at the first compression stage are set at 1.013 bar and 298 K. The isentropic efficiency of the compressors is taken as 90% and the isentropic efficiency of the gas and steam turbines is fixed at 90%. The gas turbine inlet temperature is varied between 1200 and 1700 K and the operation range for the compressor pressure ratio from 5-35 is chosen in this study. The exhaust gas temperature at the HRSG exit is maintained above the condensation temperature of combustion products. The steam conditions at the steam turbine inlet are set at 8 MPa and 400°C and the condenser pressure in the steam cycle is 0.1 bar in the condenser. Also, the

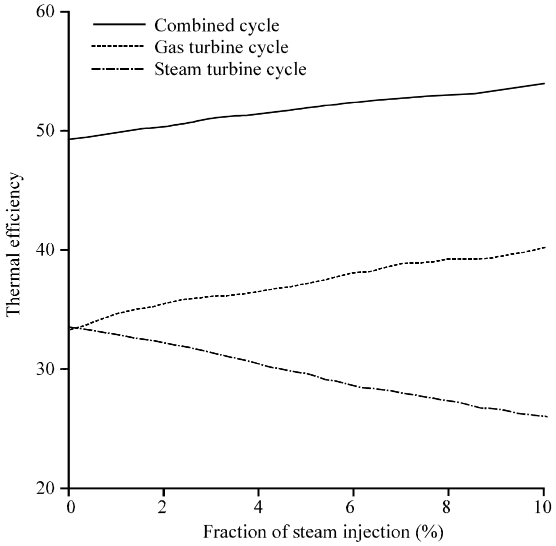

Fig. 4: Effect of fraction of steam injection on combined cycle, gas turbine cycle and steam turbine cycle efficiencies (TIT = 1450 K and rp = 20)

present study investigates the effect of the varying the isentropic efficiency of the compressors and turbines in the combined cycle. The Matlab codes have been development for thermodynamics simulation of the combined cycle with steam injection configuration.

The effect of steam injection (0-10%) with gas turbine inlet temperature set at 1500 K on the combined cycle's performance is shown in Fig. 4. An increase in the steam injection fraction led to decrease in the bottoming cycle efficiency. An increase in the extracted steam from the bottoming cycle results in lower work output due to a reduction in the utilization of the steam in the bottoming cycle with other operation conditions being fixed (Pressure ratio, TIT). However, an increase in the steam injection results in a higher topping cycle work output and efficiency and the overall combined cycle efficiency. This increased efficiencies can be attributed to the increased the mass flow rate of combustion products in the topping cycle and also variable in specific heat of the gas. Figure 4 and 5 show the variation of the combined cycle power output with various increments of steam injected in the combustion chamber. It indicates that the combined cycle has higher power output with higher mass of steam injection for all Turbine Inlet Temperatures (TIT) at a fixed value of pressure ratios. There are two ways to obtain high power output from the combined cycle which are (higher gas turbine inlet temperature and higher increment of steam injection in the combustor of topping cycle). Gas turbine cycle power outputs is higher with both higher gas turbine inlet temperature and steam injection due to additional of steam in combustor of gas turbine cycle. The gas turbine cycle dominates the high percentage of combined cycle performance. As result, a little improvement in gas turbine cycle performance either efficiency or power outputs will reflect on whole combined cycle performance. The variation of the pressure ratio and fraction steam injection on the gas turbine power output is shown in Fig. 6. The pressure ratio is varied from 5-35 and the gas turbine inlet temperature is fixed at 1450 K. Steam injection in the combustor of gas turbine cycle is varied between 0 and 10% of incoming compressed air. The gas turbine cycle power output is increased by 21% following an increase in pressure ratio and percentage of steam injection. The variation of the pressure ratio and fraction steam injection

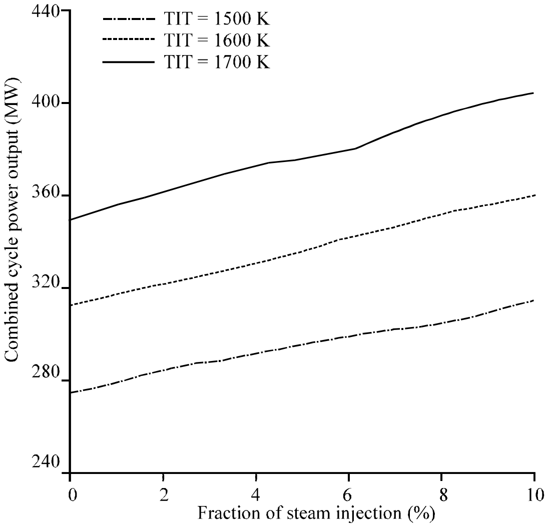

Fig. 5: Effect of fraction of steam injection on combined cycle power output with varying turbine inlet temperature

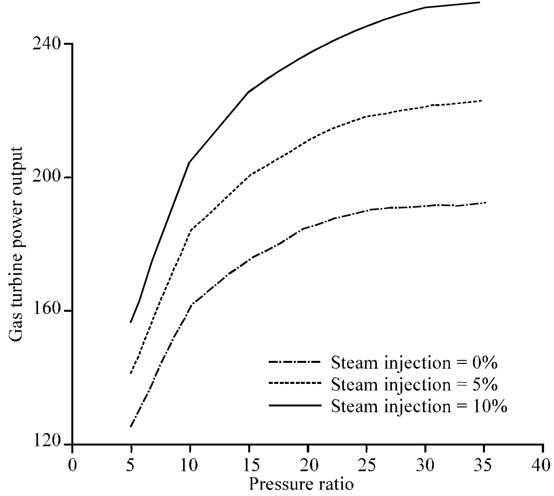

Fig. 6: Effect of pressure ratio on the gas turbine cycle power output with various fraction steam injection (TIT = 1450 K)

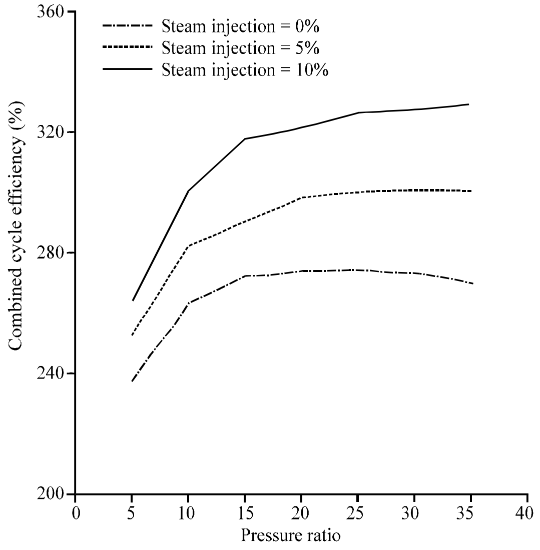

Fig. 7: The variation of the pressure ratio and fraction steam injection on the combined cycle power output (TIT = 1450 K)

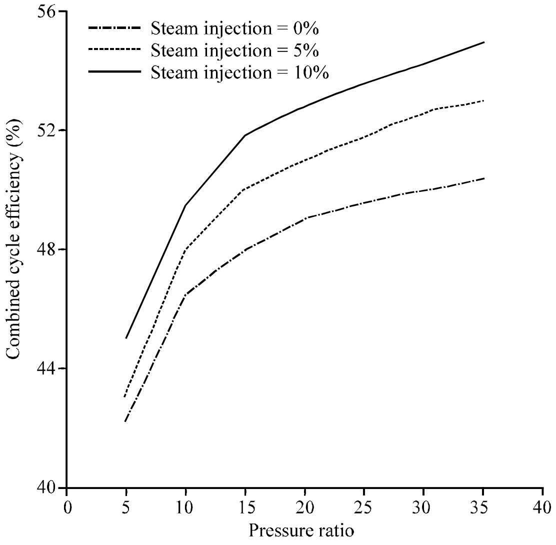

Fig. 8: Effect of the pressure ratio on the combined cycle efficiency with various fraction steam injection (TIT = 1450 K)

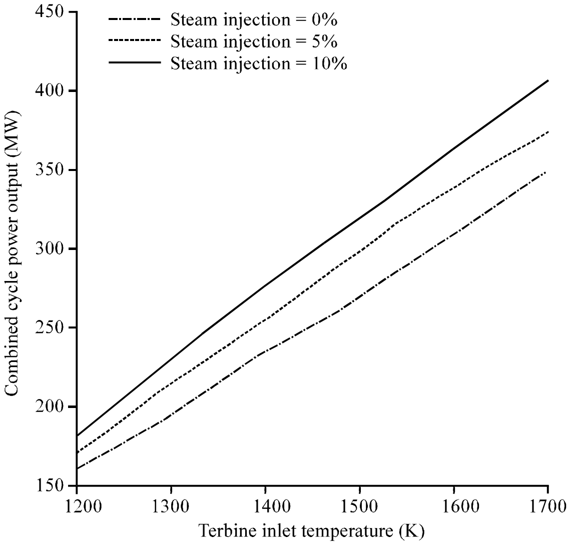

Fig. 9: Effect of turbine inlet temperature on the combined cycle power output with various amount of steam injection

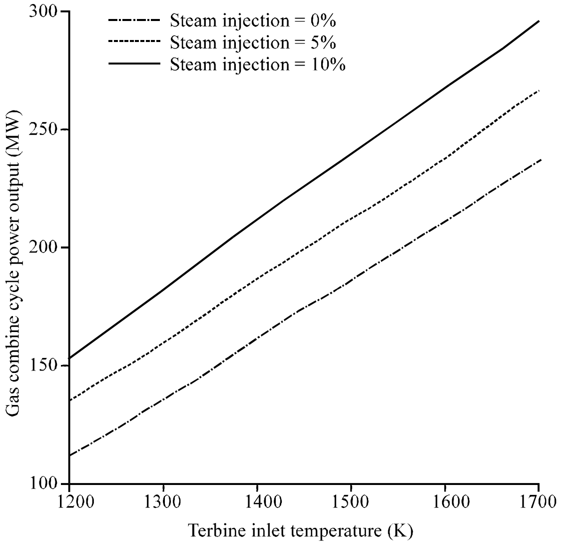

Fig. 10: Effect of turbine inlet temperature on the gas turbine cycle power output with various amount of steam injection

on the combined cycle power output is shown in Fig. 7. Figure 7 shows that a high pressure ratio and increasing the fraction of steam injection had a positive effect on the combined cycle net work output until it peaks at a particular pressure ratio and stared to decline due to increased the compressor work input and lower the power output from the gas turbine cycle. The effect of pressure ratio on the combined cycle thermal efficiency with variation in the increment of fraction of steam injection is shown in Fig. 8. The combined cycle net power output increase with increasing pressure ratio and fraction of steam injection. Obviously, higher combined cycle efficiency occurs at high pressure ratio of 30-35 with fraction of steam injection at 10%. The effect of turbine inlet temperature with various amount of steam injection on combined cycle performance including net power output and topping cycle power output is shown in Fig. 9 and 10, respectively. For a particular pressure ratio and a fraction of steam injection, an increase in turbine inlet temperature led to increases in the combined cycle net power output. Steam injection in the combustor of the gas turbine cycle has an obvious effect at high turbine inlet temperatures and small effect at low temperatures. Figure 10 shows the variation of gas turbine cycle power output with various turbine inlet temperature (1200-1700 K) at different fraction of steam injected in the combustion chamber (from 0-10% of compressed air). Figure 10 shows that gas turbine cycle power output is higher at increasing the percentage of steam injection in the combustor for each turbine inlet temperature at fixed compressor pressure ratio. The gas turbine cycle power output is increased in cycles which incorporate steam injection when compared to a similar cycle without steam injection at the same gas turbine inlet temperature. This increase can be attributed to the specific heat of combustion of the mixture as results of additional of steam in the combustion chamber.

Figure 10 shows the effect of turbine inlet temperature on gas turbine cycle power output with various fractions of steam injection. The gas turbine cycle power output increases with both turbine inlet temperature and fraction of steam injection. At higher turbine inlet temperatures and fraction of steam injection the enthalpy of the combustion mixture at the combustion chamber outlet is higher.

Furthermore for the same pressure ratio the drop in enthalpy of combustion products between the turbine inlet and outlet is higher. Also, the feed flow rate of the steam injection leads to increase the mass flow rate of the combustion mixture accordingly. This results in an increase in the power output from gas turbine cycle.

The net power output of the combined cycle, gas turbine cycle and the steam turbine cycle with the turbine inlet temperature is shown in Fig. 11. The effect of the turbine inlet temperature on the gas turbine cycle. At a fixed pressure ratio, the gas turbine exhaust temperature is higher when the gas turbine cycle operates at higher temperature. Thus, more steam generated in the Heat Recovery Steam Generator (HRSG) due to greater heat input to steam turbine cycle. Therefore, the combined cycle net power output increases with increasing turbine inlet temperature accordingly.

Also, Fig. 12 shows the relationship between the efficiencies of combined cycle, gas turbine cycle and steam turbine cycle with 5% of steam injection. This was obtained when varying the turbine inlet temperature for a pressure ratio of 22. Obviously, gas turbine cycle, steam turbine cycle and combined cycle efficiency increased with higher Turbine inlet temperature due to increasing net power output from both gas turbine cycle and steam turbine cycle.

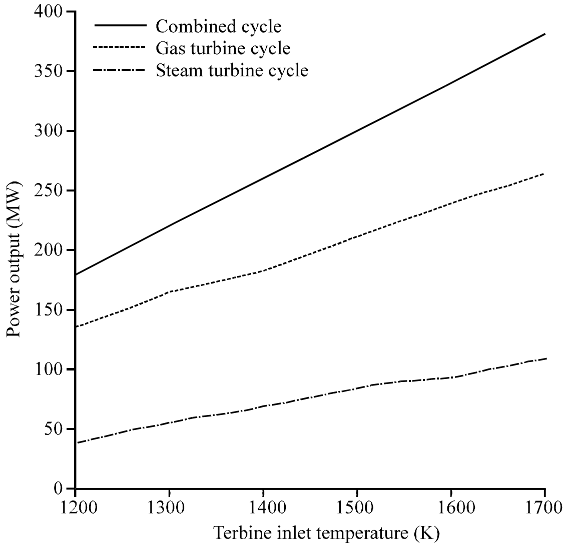

Fig. 11: Effect of turbine inlet temperature on gas turbine cycle, steam turbine cycle and combined cycle power outputs

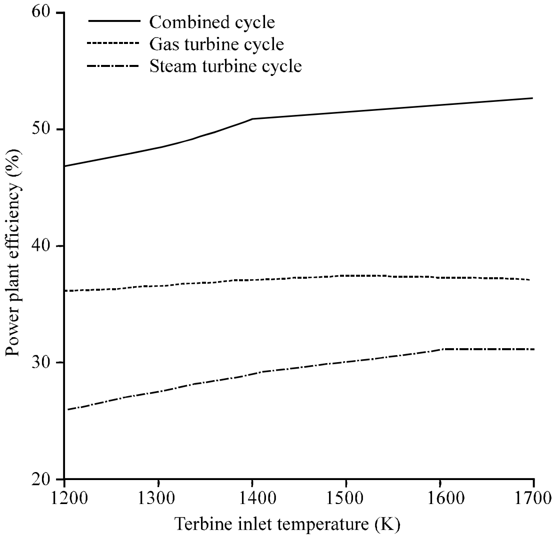

Fig. 12: Effect of turbine inlet temperature on gas turbine cycle, steam turbine cycle and combined cycle efficiency

CONCLUSION

In this study, the performance characteristics of the combined cycle power plant with three different configurations including steam injection and component efficiencies have been analyzed. Simulation codes are written to investigate the effect of different operating parameters which include fraction of injected steam, the turbine pressure ratio and Turbine Inlet Temperature (TIT) of topping cycle. At a particular pressure ratio and turbine inlet temperature, an increase in the steam injection fraction led to decrease in the steam turbine cycle efficiency. An increase in the extracted steam from the steam turbine cycle results in lower power output. However, an increase in the steam injection results in a higher gas turbine cycle power output and efficiency and the overall combined cycle efficiency.

For particular fraction of steam injection and turbine inlet temperature, increasing the gas turbine pressure ratio results in higher net power outputs until optimum pressure ratio is reached. Increasing the pressure ratio has positive effect on the overall efficiency of combined cycle power output. At specific pressure ratio and fraction of steam injection, an increase in gas turbine inlet temperature leads to increases in the gas turbine cycle, steam turbine cycle and combined cycle power plant net power outputs.

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