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Thermal influence of ambient air temperature on performance of combined cycle power plant

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Abstract
The power output and efficiency of gas turbine is a strong function of the ambient air temperature. In hot climatic condition the mass flow rate of air decreases with increasing ambient air temperature for the same volumetric flow rate, which results in reduction in power output and efficiency of turbine. The present paper deals with the study of effect of ambient air temperature on various parameters of 415 MW combined cycle power plant. The results of analysis reveals that for an increase in ambient air temperature by 40^0C, the net power output of the gas turbine and combined cycle is found to decrease by 29.16% and 23.68% with 12.79% decrease in mass flow rate of inlet air. The efficiency of the gas turbine and combined cycle is found to decrease by 8.5% and 1.5% for the same increase in ambient air temperature.

Keywords: gas turbine, combined cycle, inlet air temperature, power output, heat recovery steam generator

1. Introduction
The gas turbine performance depends on various operating parameters of the plant. The inlet air temperature is one of the key parameter that greatly influences the power output and efficiency of gas turbine. In hot climatic conditions the power output and efficiency of gas turbine is less than that of during cold condition because of inverse relation between the air density and temperature. Cooling the inlet air of gas turbine, decreases the temperature which increases the air density, hence increases the mass flow rate of air.
Therefore ability to cool the inlet air will facilitate the production of constant gas turbine power output throughout the year, irrespective of the change in ambient temperature. Cooling the inlet air increases the mass flow rate of air into the gas turbine and at the exhaust outlet. The increased exhaust mass flow increases the steam generation rate in the heat recovery steam generator downstream of the gas turbine due to higher energy availability in the exhaust gas

2. Thermodynamic Modeling
The schematic diagram of dual pressure combined cycle under consideration is shown in figure.1. In this arrangement a simple gas turbine cycle is used as topping cycle and a steam cycle is used as bottoming cycle. The waste heat of gas turbine exhaust which is at high temperature is recovered in a dual pressure heat recovery steam generator.
The temperature – Entropy diagram for the combined cycle is shown in figure 2.

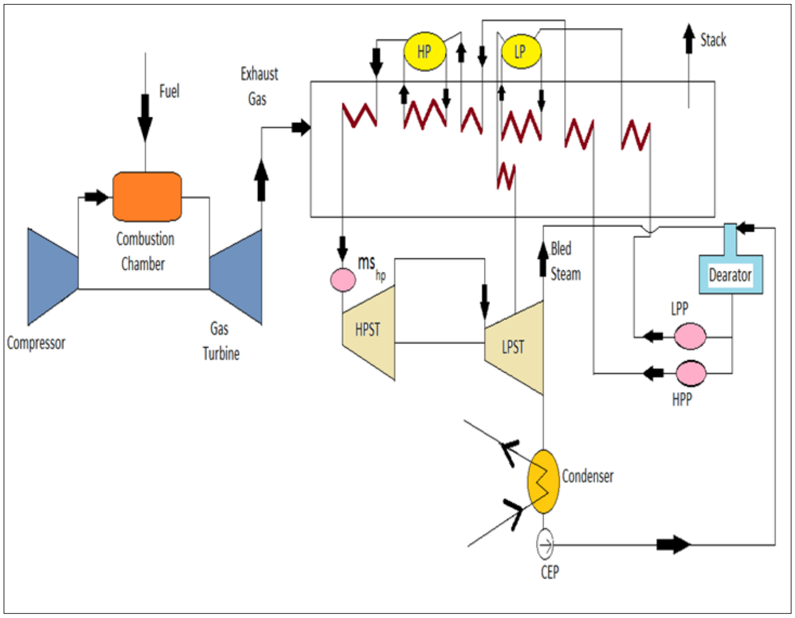

Fig 1: Schematic Diagram of Combined cycle Power Plant

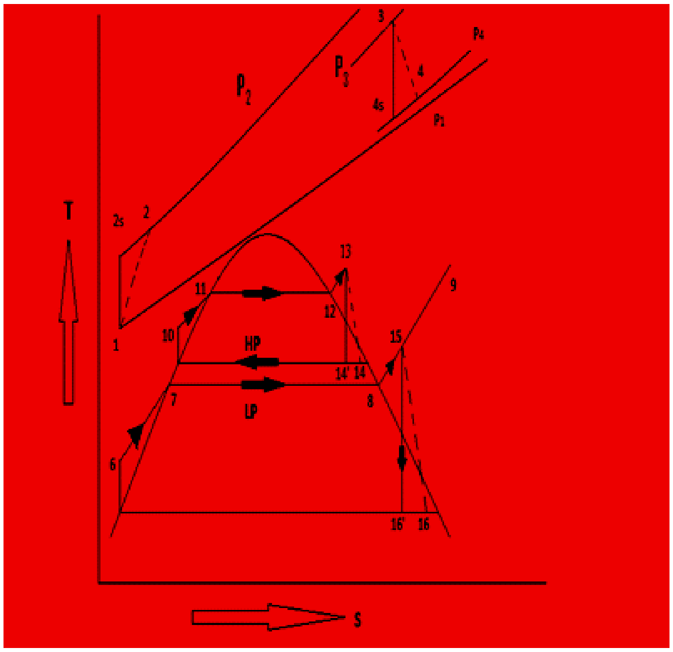

Fig 2

2.1Gas turbine cycle model

It is assumed that the compressor efficiency and the turbine efficiency are represented by η_c and η_t respectively. The ideal and actual processes are represented by full and dashed lines on the temperature entropy diagram as shown in figure 2.

Air compressor model

The compression ratio R_P of the compressor can be defined as

$$r_p = \frac{P_2}{p_1} \qquad (1)$$

Where P_1 and P_2 are compressor inlet and outlet pressures respectively

The isentropic efficiency of compressor is expressed as

$$\eta_c = \frac{T_{2S} - T_1}{T_2 - T_1} \qquad (2)$$

Where

T_1 = compressor inlet temperature

T_{2S} = compressor isentropic outlet temperature

T_2 = compressor actual discharge temperature

The actual discharge temperature of the compressor is calculated from eq 3

$$T_2 = T_1 + \frac{T_{2S} - T_1}{\eta_c} \qquad (3)$$

The work of the compressor (W_C) can be calculated as

$$W_C = \dot{m}_a \times c_{pa} \times (T_2 - T_1) \qquad (4)$$

Where C_{pa} is the specific heat of air which can be fitted by eq 5 for the range of 200K< T<800K.

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

Combustion chamber model

From the energy balance in the combustion chamber

$$\dot{m}_a C_{pa} T_2 + \dot{m}_f \times LHV + \dot{m}_f C_{pf} T_f = (\dot{m}_a + \dot{m}_f) C_{pg} \times TIT \qquad (6)$$

Where $\dot{m}_f$ is the fuel mass flow rate (kg/s), $\dot{m}_a$ is the air mass flow rate(kg/s), LHV is the lower heat value, TIT = T_3 is turbine inlet temperature, c_{pf} is the specific heat of fuel and T_f is the temperature of the fuel, and c_{pg} is the specific heat of flue gases.

The specific heat of flue gases c_{pg} is given by eq (7)

$$C_{pg} = 1.8083 - 2.3127 \times 10^{-3} T + 4.045 \times 10^{-6} T^2 - 1.7363 \times 10^{-9} T^3 \qquad (7)$$

The fuel air ratio (f) is expressed as Eq 8

$$f = \frac{\dot{m}_f}{\dot{m}_a} = \frac{C_{pg} \times TIT - C_{pa} \times T_2}{LHV - C_{pg} \times TIT} \qquad (8).$$

Gas turbine model

The isentropic efficiency of gas turbine is given by Eq (9)

$$\eta_t = \frac{T_3 - T_4}{T_3 - T_{4s}} \qquad (9)$$

Where

T_3 = Turbine inlet temperature

T_{4s} = isentropic discharge temperature of gas turbine

T_4 = actual discharge temperature of gas turbine

The actual discharge temperature of gas turbine can be given by Eq (10)

$$T_4 = T_3 - \eta_t (T_3 - T_{4s}) \qquad (10)$$

The shaft work of the gas turbine is given by Eq (11)

$$W_{GT} = \dot{m}_g \times C_{pg} (T_3 - T_4) \qquad (11)$$

The network of the gas turbine is determined by Eq (12)

$$(W_{GT})_{net} = W_{GT} - W_C \qquad (12)$$

The specific fuel consumption is determined by Eq (13)

$$sfc = \frac{3600 \times \dot{m}_f}{(W_{net})} \qquad (13)$$

The heat supplied is given by Eq (14)

$$Qadd = \dot{m}_f \times LHV \qquad (14)$$

The thermal efficiency of gas turbine is determined by Eq (15)

$$(\eta_{th})_{GT} = \frac{(W_{GT})net}{\dot{m}_f \times LHV} \quad (15)$$

Steam turbine cycle model

It is assumed that the steam turbine efficiency and pump efficiency are represented by η_{st} and η_p respectively. The ideal and actual processes on temperature – Entropy diagram are represented by full and dashed lines as shown in figure.

Heat recovery steam generator model

A dual pressure HRSG is considered here for combined cycle gas turbine plant. By applying energy balance for gas and water in each part of the HRSG the gas temperature and water properties are calculated by solving the following equations,

Heat available with the exhaust gases from gas turbine is given as

$$Q_{av} = \dot{m}_g \times C_{pg} \times (T_4 - T_5) \times h_{f1} \quad (16)$$

Where T_5 is the exhaust temperature of the flue gases from HRSG, and h_{f1} is the heat loss factor whose value ranges from 0.98 to 0.99.

The HP superheater duty is expressed as

$$(Q_{sh})_{HP} = ms_{HP}\,(h_{13} - h_{12}) = \dot{m}_g \times c_{pg} \times (T_4 - T_g) \quad (17)$$

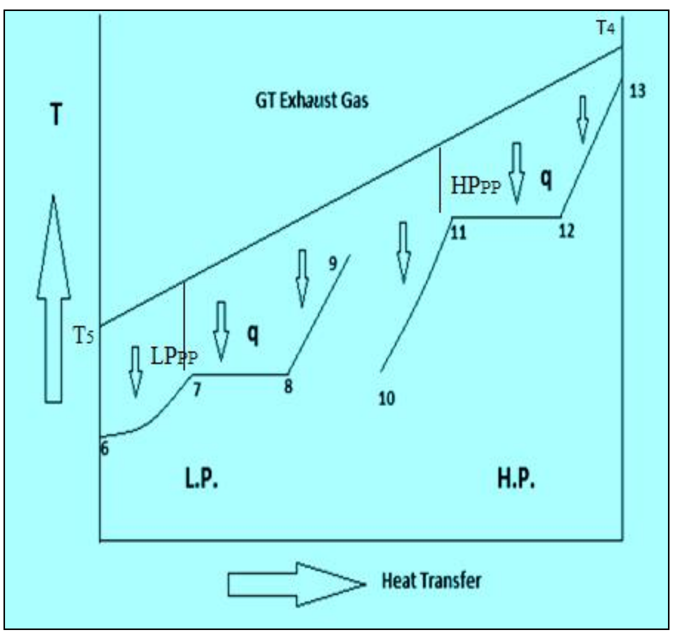

Fig 3: Temperatures – heat transfer diagram of HRSG

The thermal analysis of HRSG depends on the designed pinch point $(\Delta T)_{PP}$ and approach point$(\Delta T)_{AP}$. The temperature of the gas leaving the HP evaporator is given by Eq 18

$$T_{g1} = T_{11} + (\Delta T_{PP})_{HP} \quad (18)$$

Where T_{11} is the saturation steam temperature corresponding to HP superheater pressure and $(\Delta T_{PP})_{HP}$ is the pinch point temperature difference in the HP side of HRSG.

The LP superheater duty is expressed as

$$(Q_{sh})_{LP} = ms_{LP}\,(h_9 - h_8) = \dot{m}_g \times c_{pg} \times (T_{g1} - T_{g2}) \quad (19)$$

The temperature of the hot exhaust gases leaving the HRSG is given as

$$ms_{LP}\,(h_9 - h_6) + ms_{HP}\,(h_{11} - h_{10}) = \dot{m}_g \times c_{pg} \times (T_{g1} - T_5) \quad (20)$$

Steam turbine model

The steam at high pressure and high temperature obtained from HP superheater is expand in the HP steam turbine and then mixed with LP steam obtained from LP superheater and expand upto the condenser pressure in LP steam turbine. The energy balance gives

$$W_{HPST} = ms_{HP}\,(h_{13} - h_{14}) \quad (21)$$

$$W_{LPST} = ms_{HP} + ms_{LP}\,(h_{15} - h_{16}) \quad (22)$$

Condenser Model

The heat rejected from the condenser is expressed as

$$Q_{rej} = (ms_{HP} + ms_{LP} - ms_{bled})\,(h_{16} - h_{f17}) \quad (23)$$

Pump Model

The condensate from the condenser is extracted by the HP and LP pump and raised to LP and HP economizer pressure. The corresponding work is given by

$$W_{hpp} = m_w \times v_{17}\,(p_{10} - p_c) \quad (24)$$

$$W_{lpp} = m_w \times v_{17}\,(p_6 - p_c) \quad (25)$$

Therefore the net work of ST power plant is

$$(W_{net})_{ST} = W_{ST} - W_P \quad (26)$$

The efficiency of steam turbine power plant is

$$\eta_{st} = \frac{(Wnet)st}{Q_{av}} \quad (27)$$

The overall thermal efficiency of the combined cycle gas turbine plant is given by

$$\eta_{cc} = \frac{(W_{net})GT + (W_{net})ST}{\dot{m}_f \times LHV} \quad (28)$$

3. Results and Discussion

The power output, efficiency and mass flow rate for gas turbine, steam turbine and combined cycle were calculated for various ambient air temperatures and results of analysis are presented in figures given below.

Figure 4 shows the variation of mass flow rate of air in the compressor with inlet air temperature to the compressor. It is seen that the mass flow rate of air decreases by12.79% as the inlet air temperature increases from 273K to 313K. This is due to the fact that mass flow rate of air m_a = pv/RT is inverse linear function of temperature m_a = 1/f(T) for a constant value of P, V, and R. The volumetric flow to most of the compressors is constant, therefore mass flow rate of air decreases as inlet air temperature increases because of decreased density of air

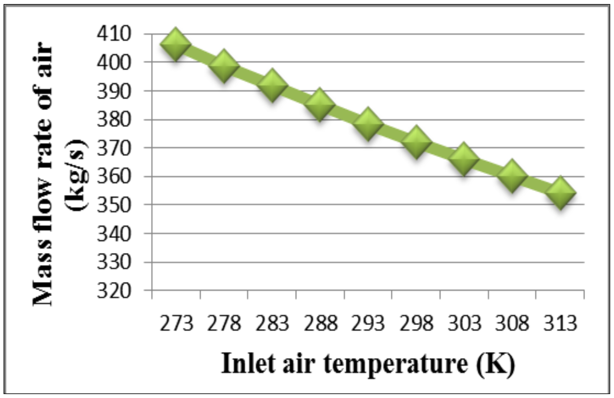

Fig 4: Effect of inlet air temperature on mass flow rate of air

Figure 5 shows the variation of net power output of the gas turbine with inlet air temperature. It is seen that the net power output of the gas turbine decreases by 29.16% as the inlet air temperature increases from 273K to 313K. This is due to the fact that compressor work is directly proportional to inlet and outlet temperature difference of compressor and mass flow rate of air. The temperature difference is directly proportional to inlet air temperature T_1. With decreasing inlet air temperature the outlet temperature of compressor decreases and the difference of temperatures also. This decreases the compressor work. Similarly the gas turbine output is directly proportional to inlet and outlet temperature difference of turbine and mass flow rate of air and fuel. Since the difference of inlet and outlet temperature of gas turbine remain constant for a given pressure ratio and TIT, The gas turbine output decreases due to the decreased mass flow rate of air with increasing inlet air temperature.

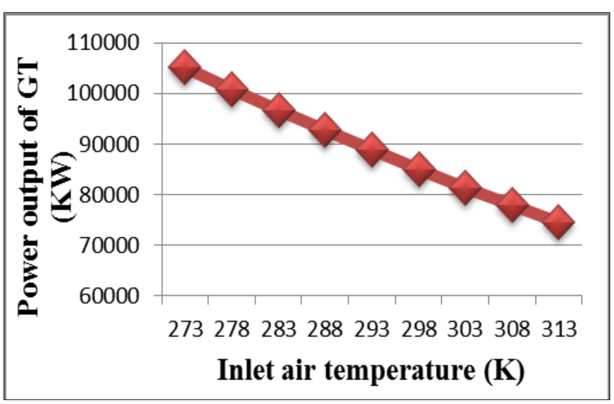

Fig 5: Effect of inlet air temperature on power output of GT

Figure 6 shows the variation of gas turbine efficiency with inlet air temperature. It is clear from the figure that the gas turbine efficiency decreases by 8.5% as the inlet air temperature to compressor increases from 273K to 313 K. This is due to the fact that the gas turbine efficiency is directly proportional to the net output of the gas turbine and is inversely proportional to the heat supplied in the combustion chamber of gas turbine. The net power output of gas turbine decreases with increase in inlet air temperature because of increasing compressor work and decreasing turbine work due to decreased mass flow rate of air. The heat supplied in combustion chamber also decreases with increasing inlet air temperature, but the reduction in heat supplied is less than the reduction in net power output of gas turbine, therefore the efficiency of gas turbine decreases with increase in inlet air temperature to compressor.

Figure 7 and 8 shows the effect of inlet air temperature to the compressor of gas turbine on the mass flow rate of steam to the HP and LP steam turbine. It is observed that the mass flow rate to both HP and LP turbine decrease with increase in the inlet air temperature of compressor. This is due to the fact that the mass flow rate through the gas turbine decreases with increasing inlet air temperature, therefore less heat is available at the exhaust of gas turbine to utilize in the waste heat recovery steam generator for a given exhaust temperature of gas turbine. It is clear from the figure that the mass flow rate to the HP steam turbine decreases by 12.98% when the inlet air temperature increases from 273K to 313 K. Similarly the mass flow rate to LP steam turbine decreases by 12.98% for the same increase in compressor inlet temperature.

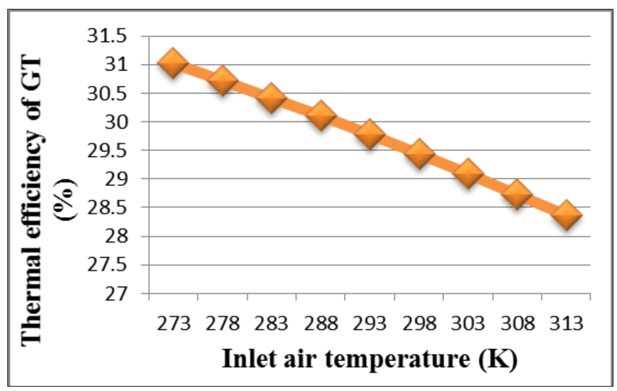

Fig 6: Effect of inlet air temperature on thermal efficiency of GT

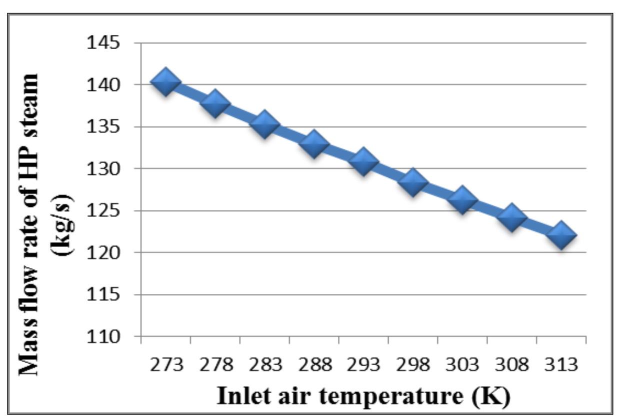

Fig 7: Effect of inlet air temperature on mass flow rate of HP steam

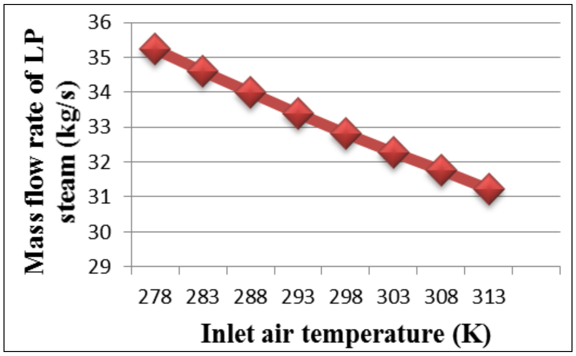

Fig 8: Effect of inlet air temperature on mass flow rate of LP steam

Figure 9 shows the effect of inlet air temperature to compressor on the power output of the HP and LP steam turbine. It is clear from the figure that the power output of both HP and LP steam turbines decreases with increase in inlet air temperature to compressor due to decreased mass flow rate of steam. It is observed that the power output of HP steam turbine is decreases by 12.98% as the inlet air temperature increases from 273K to 308K. Similarly the power output of LP steam turbine decreases by 13.28% for the same increase in inlet air temperature.

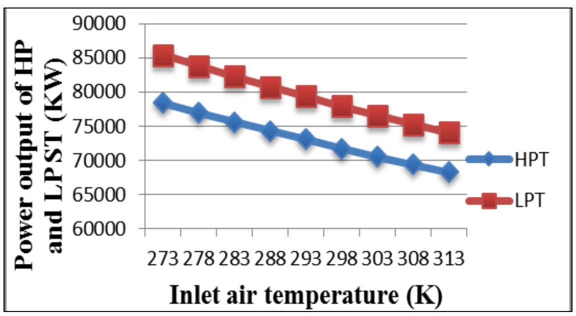

Fig 9: Effect of inlet air temperature on power output of HP and LP steam turbine

Figure 10 shows the effect of inlet air temperature to compressor on the power output of combined cycle. It is clear from the figure that the power output of combined cycle decreases by 23.68% as the inlet air temperature increases from 273 K to 313 K. This is due to the fact that with increase in inlet air temperature the mass flow rate through gas turbine decreases which result in reduction of gas turbine output. In addition to this the steam turbine output also decreases because of reducing steam flow rate.

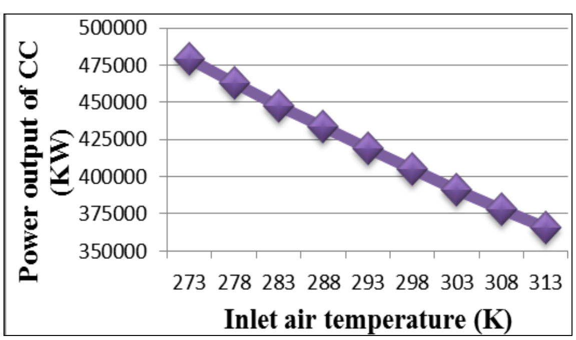

Fig 10: Effect of inlet air temperature on power output of combined cycle

Figure 11 shows the effect of inlet air temperature to compressor on the thermal efficiency of combined cycle. It is clear from the figure that the thermal efficiency of combined cycle decreases by 1.5% as the inlet air temperature increases from 273 K to 313 K. The reason behind this is that both gas turbine and steam turbine outputs decreases with increasing inlet air temperature. The reduction in combined cycle efficiency is less compared to the reduction of gas turbine efficiency for the same range of increasing inlet air temperature because of insignificant change in steam cycle efficiency with varying inlet air temperature.

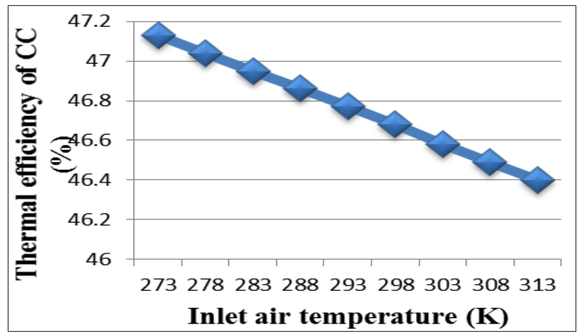

Fig 11: Effect of inlet air temperature on thermal efficiency of combined cycle

4. Conclusions

The effect of increase in inlet air temperature from 0^0C to 40^0C gives the following observation and conclusions

1. Mass flow rate of air is decreases by 12.79% for given increase in inlet air temperature
2. The net power output of gas turbine is found to decrease by 29.16% and gas turbine efficiency is decreased by 8.5%.
3. The power output from steam turbine is found to decrease by 13% and the mass flow rate of steam is decreased by 12.98%.
4. The efficiency of combined cycle is found to decrease by 1.5% along with 23.68% reduction in power output.
5. The combined cycle plant capacity is found to decrease by 100MW in summer when average inlet air temperature is 40^0C.

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