Design of Chiller Type Inlet Air Cooling System to Enhance the Performance of Combined Cycle Power Plant

[1]Panchalinge Gowda. H. L
M.Tech. student (Thermal Power Engg.),
Dept. of Mechanical Engg. SIT,
Tumkur, India

[2]Dr. N. S. Venkatesha Gupta
Associate Professor,
Dept. of Mechanical Engg, SIT,
Tumkur, India

[3]Somasundaram. R
Sr.Manager,
Tata Consulting Engineers Ltd.,
Bangalore, India.

***Abstract*— Industrial gas turbines that operate at constant speed are constant-volume-flow combustion machines. As the specific volume of air is directly proportional to the temperature, the increase of air density results in a higher air mass flow rate, once the volumetric rate is constant. Consequently, the gas turbine power output enhances. It was estimated that in reduction of 1°C temperature of inlet air increases the power output by approximately 0.7 MW. For geographic regions where significant power demand and highest electricity prices occur during the warm months, a gas turbine inlet air cooling technique is a useful option for increasing the plant output. Inlet air cooling system increases the power output by taking advantage of the gas turbine's feature of higher mass flow rate, due to the compressor inlet temperature decays. Different methods are available for reducing compressor intake air temperature, out of which vapor absorption machine is also one. In this study hot water based vapor absorption machine is selected for cooling the inlet air of 350 MW combined cycle power plant. The chilled water produced by vapor absorption machine flows through a heat exchanger located at upstream of inlet air duct to reduce the air temperature from 33°C to 25°C.In the present study, the thermodynamic analysis of gas turbine performance is carried out to calculate heat rate, power output and thermal efficiency at reduced inlet air temperature condition. The thermodynamic analysis is done by using the plant simulation software THERMOFLOW, which is used for power plant design. The results obtained with this model are compared with the values of the condition without inlet air cooling system herein named as site condition. The effects on other parameters of combined cycle power plants (CCPP) due to above modification are estimated and payback period is estimated for the total investment made on the turbine inlet air cooling system. Based on the simulation and the calculation, it is estimated that the total investment cost for this Type Inlet Air Cooling system will be about Rs. 398 Lakhs and the payback period will be about 4.9 years with a ROE of 16 percent.**

Keywords—: Combined Cycle Power Plant, Turbine inlet air cooling system, Vapor absorption machine, efficiency, heat rate.

1.0. INTRODUCTION

Combustion turbines or Gas turbines (GT) are constant volume machines, i.e. air intake is limited to a fixed volume, regardless of ambient air conditions. As air temperature rises, its density falls. Thus, although the volumetric flow rate remains constant, the mass flow rate is reduced as the temperature of air increases. This results in reduction of Power output, as power output is proportional to mass flow rate. The conversion efficiency of the gas turbine also falls as air temperature rises because more power is required to compress the warmer air.

Therefore increasing the air density increases the mass flow rate. By ignoring the additional mass flow from the fuel, an ideal gas the mass flow rate is:

$m = P_1V_1 / RT_1$, Where m-Mass flow rate, P-Pressure, R-Gas constant, T-Temperature, V-Volumetric flow rate.

Power output is a linear inverse function of temperature. As the inlet air temperature increases, such as on hot summer days, the capacity of the turbine decreases. If the inlet air is cooled to a lower temperature, the power increases, along with increased efficiency (decreased heat rate). The cycle efficiency, η, can be expressed in terms of the isentropic compression process from compressor inlet temperature, T_1, to compressor outlet temperature, T_2, as:

$\eta = 1 - (T_1/T_2)$ where, η-Thermodynamic efficiency

By decreasing T_1, the efficiency increases. The effect of ambient temperature to the power output and efficiency of gas turbine is indicated in Fig.1.1.

Gas turbine site performance is directly affected by inlet air density and air environmental conditions. As explained above, performance of GT improves with lower inlet air temperature. Considering the same, to enhance the performance of the combined cycle, in this project, the inlet air temperature is decreased using the vapor absorption chiller (which utilizes the hot water from the Heat Recovery Steam Generator). The performance optimization of CCPP unit is carried out using power plant simulation software THERMOFLOW®.

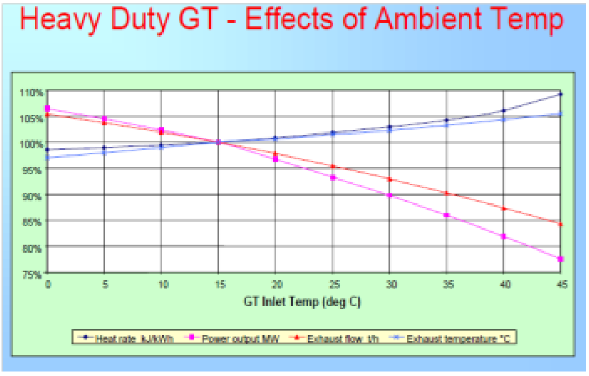


Fig.1.1 Effects of ambient temperature on heavy duty Gas turbine performance

(Source: www.turbineinletcooling.org)

2.0 OBJECTIVE AND METHODOLOGY

The main objective of this study is to analyze, optimize and improve the performance of combined cycle power plant by decreasing inlet air temperature of the gas turbine closer to ISO condition (say 25°C). In combined cycle power plant, Heat Recovery Steam Generator (HRSG) is one of the main components, in which hot gas is used to heat the feed water to a high quality steam. In the process of converting water in to saturated steam, the temperature of water rises inversely with GT exhaust gas temperature.

As shown in the typical process flow diagram Fig 2.1, feed water flows in series connection as per the following order: Condensate Extraction Pump (CEP)-Condensate preheater-Deaerator-Economizer-Evaporator-HP/IP/LP drums-Super heater/Reheater coils-HP/IP/LP Turbine-condenser-CEP. Temperature of feed water is different in different stages of process flow and also in increasing order.

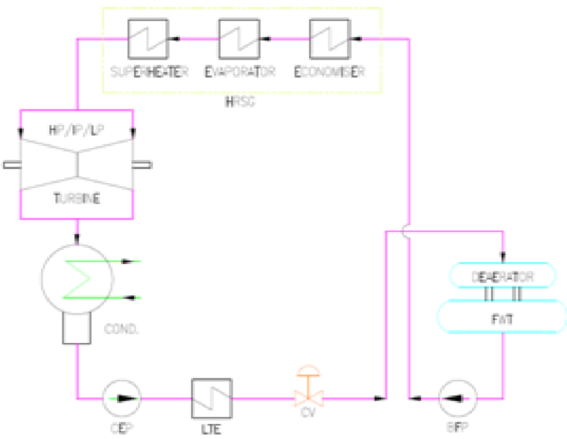


Fig.2.1 Typical process flow diagram of CCPP

In this study, it is proposed to source high temperature hot water from the condensate preheater outlet (low temperature economizer) to a hot water Vapor Absorption Machine (VAM) system and then connect the exit to Deaerator instead of directly connecting the condensate preheater outlet to Deaerator. The proposed scheme of process flow is as shown in Fig.2.2.

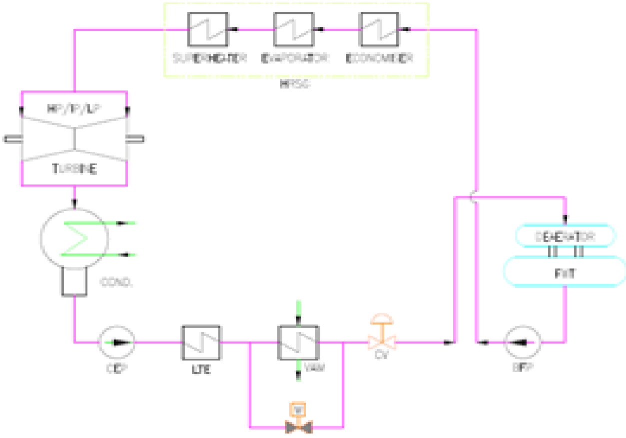


Fig.2.2 Process flow diagram with proposed modification

3.0. CCPP PERFORMANCE WITHOUT CHILLER

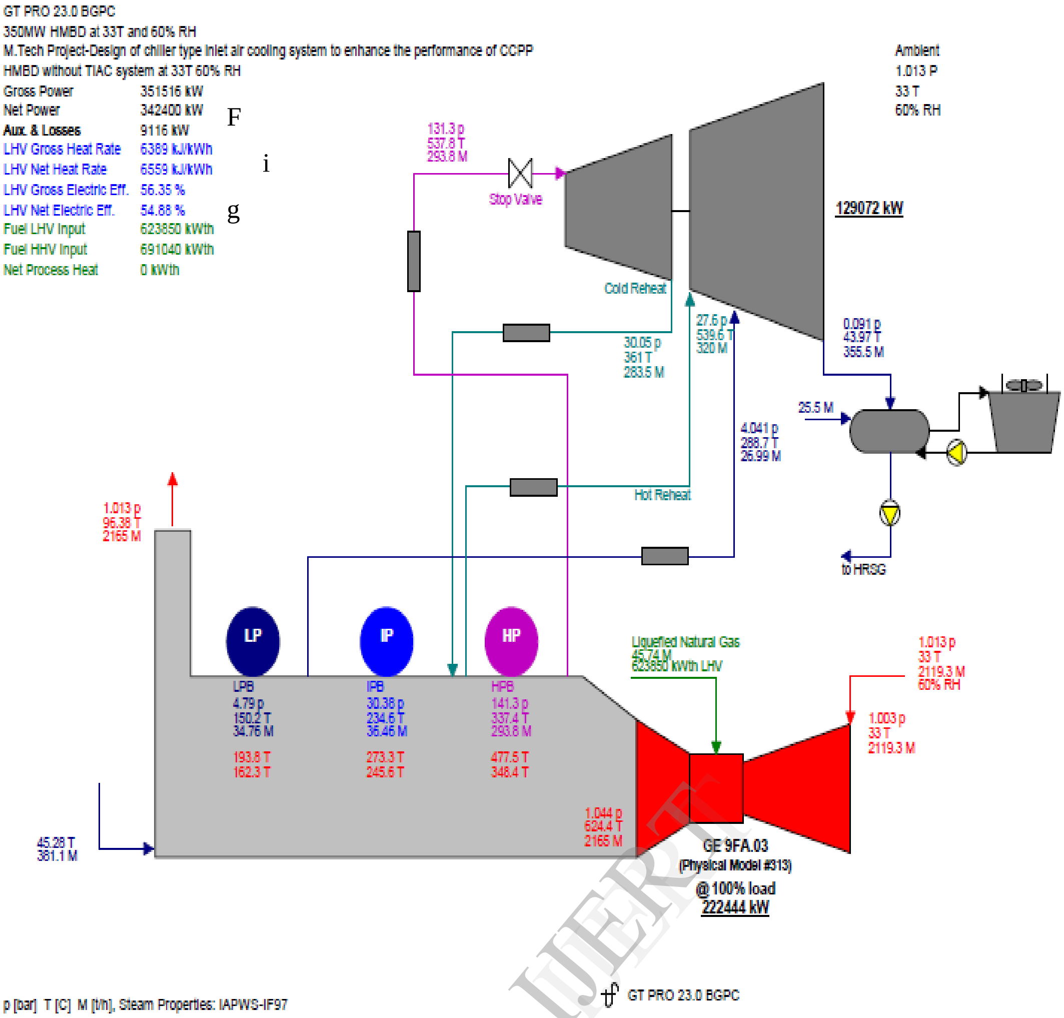
3.1 *Plant Overview*

A typical 350 MW CCPP unit with a configuration of 1 GTG + 1 HRSG + 1 STG in multi-shaft arrangement (i.e. GT and ST are connected to separate generator) is considered for the study. The site ambient condition is selected as 33°C and 60% RH. Gas turbine is selected from GE Model No. S109 FA having a gross site output of about 351.43 MW. The above configuration comprises one gas turbine generator rated for about 254.1 MW (Site output of 222.43 MW), one matching triple pressure heat recovery steam generator and one steam turbine generator rated for about 141.8 MW (Site output of 129.00 MW) under ISO condition. The fuel used for the above plant is Liquefied Natural Gas (LNG).

3.2 Heat and Mass Balance Diagram (HMBD) for Site Condition

A Heat and Mass Balance Diagram (HMBD) represents every process stream on the corresponding Process Flow Diagram (PFD) in terms of the process conditions. Normally a heat and mass balance sheet reports the critical process stream data's like, operating temperature and pressure, volumetric or mass flow rate and enthalpy flow for each stream.

The graphical simulation output of HMBD at site condition obtained from THERMOFLOW® is shown in Fig.3.2. The plant Gross electrical output at site condition is about 351.5 MW, with an electrical efficiency of 56.35%, with condenser pressure as 0.091 bar (g). The selected GT was from GE frame 9FA, with an ISO output of 395.9 MW, with a triple pressure HRSG. However these parameters can be further improved by adopting the GT inlet air cooling system



3.1 Graphical simulation output of 350MW CCPP plant at site ambient condition

4.0. CCPP PERFORMANCE WITH CHILLER

4.1 TIAC System Modeling

Turbine Inlet Air Cooling System (TIAC) is used for cooling the GT inlet air. The TIAC system is modeled using THERMOFLOW® software. Schematic diagram of TIAC system as shown in Fig.4.1 consists of-

- Vapor absorption machine with inbuilt Condenser, Generator, Evaporator, and absorber.
- Chilled water system including chilled water pump, Chilled water to air heat exchanger, piping and valves.
- Condenser cooling water piping and valves.
- Hot water line-from LTE outlet to VAM and return from VAM to Deaerator.

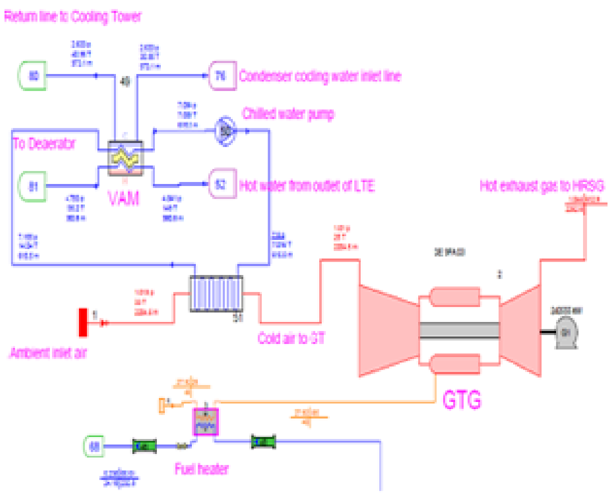


Fig.4.1 Schematic diagram of Turbine inlet air cooling system

4.2. VAM TR Estimation

The mass flow rate and enthalpy of GT inlet air to be cooled, decides the capacity of the vapor absorption machine to be envisaged. Hence the capacity of Vapor Absorption Machine (VAM) required for cooling the inlet air from ambient (33°C) to 25°C is estimated as per Table 4.2.

Description	**Unit**	**Value**
Mass flow rate air to be cooled at GT inlet (M_a)	Kg/hr	2204000
Air temperature at site condition at 60% RH	°C	33
Enthalpy of air at site condition (H_{hr})	kJ/kg	82.20
Air temperature after cooling	°C	25
Enthalpy of air after cooling (H_{ca}) at 100%RH	kJ/kg	76.20
Total heat to be removed from the inlet air	kcal/hr	3158499
Total heat to be removed in terms of TR (ITR=3024 kcal)	TR	1044.48
Total heat to be removed in terms of TR with15% margin	TR	1201.15
Next available VAM rating in the market	TR	1400

Table 4.2 Vapor absorption machine capacity calculation

4.3 Chilled water capacity Estimation

One tones of refrigeration is equal to 3.52 kW. Total heat available for cooling can be estimated using the heat transfer formula; $Q_{cw} = M_{cw} * C_{pcw} * (T_{cw2}-T_{cw1})$, Where, Q_{cw} is the heat load available for cooling in kW, M_{cw} is the mass of chilled water in kg/sec, Cpcw is the specific heat of chilled water =4.2 kJ/kg °C (assumed same as at ambient temperature), T_{cw2}-T_{cw1} is the difference of chilled water inlet and outlet temperature =15-10=5 °C.

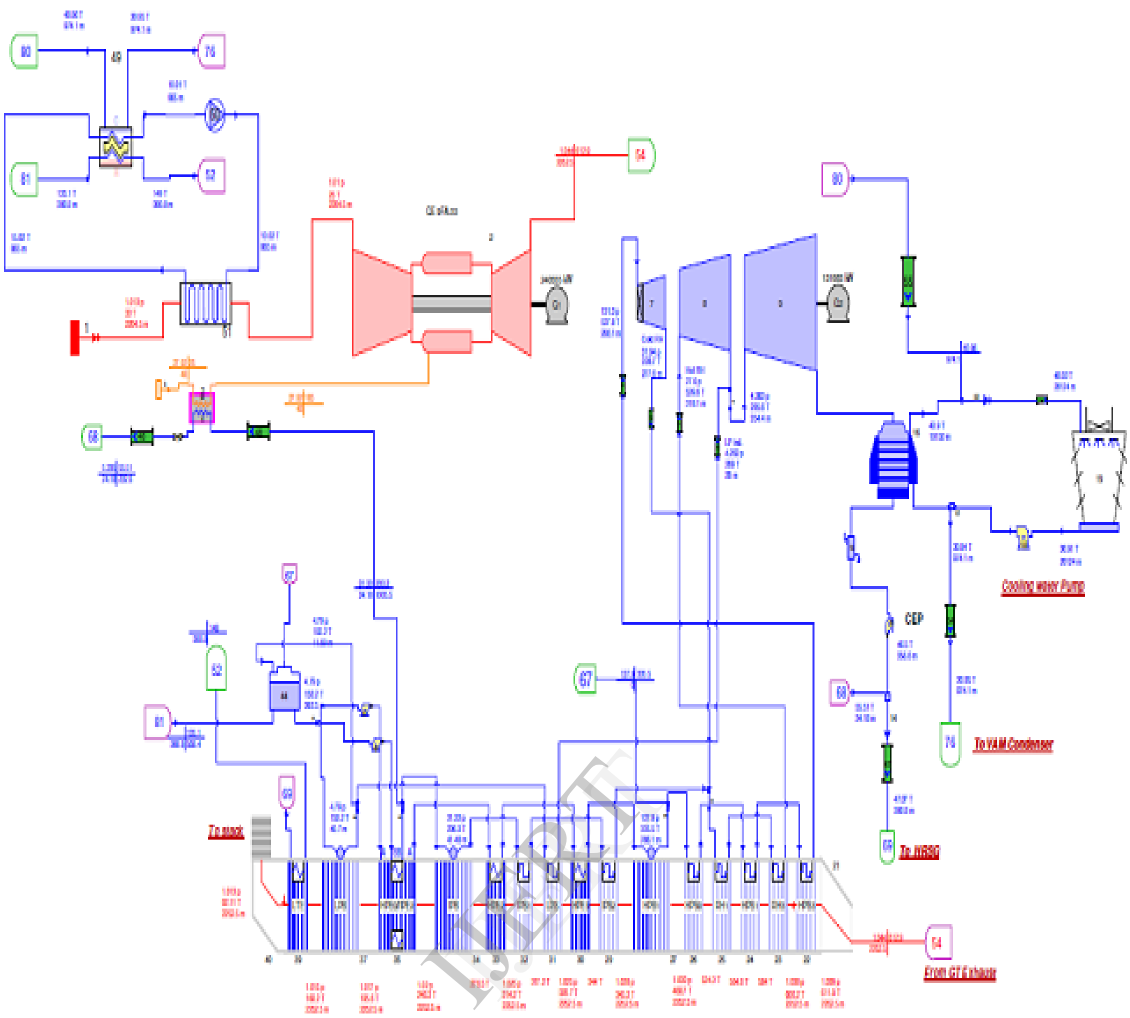
Description	**Unit**	**Value**
Mass flow rate for one TR can be calculated as	Kg/sec	0.1676
Mass flow rate for one TR in m3/hr	m^3/hr	0.603
Mass flow rate for one TR in m3/hr with 10% margin	m^3/hr	0.6637
Chiller capacity will be calculated as	m^3/hr	----
Chiller flow if 1000 TR is selected	m^3/hr	980

Table 4.3. Calculation of chiller flow capacity

4.4 HMBD for Chilled GT Inlet Condition

HMBD of modified CCPP unit along with TIAC system is developed by simulating in the THERMOFLOW® and Graphical output for the same is shown in Fig 4.4.

From the below THERMOFLOW® simulation output, total power output of the plant and gross efficiency is about 372.24 MW and 56.85% respectively which is about 5.9% increase in power output and 0.56% point increase in efficiency compared to CCPP performance parameter at site condition without the GT inlet air cooling system.



FFig 4.4. HMBD of CCPP with Turbine inlet air cooling system

GT power output (240.55 MW) alone, is about 18.11 MW more than the Gas turbine which is operating at site condition. The power output of steam turbine is marginally increased due to increase in the GT exhaust gas mass flow rate. Chilled water flow considered by TIAC system of THERMOFLOW® is marginally less than the calculated value of 980 m3/hr which is designed with additional margin.

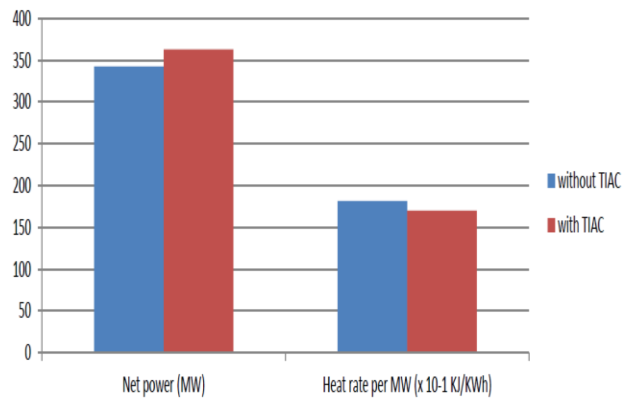
5.0. RESULTS AND DISCUSSIONS

5.1 Technical Analysis of Inlet Air Cooling System

The basis of most design decisions is economics. Designing a system that functions properly is only one part of the engineer's task. The system must also be economical and show an adequate return on investment. Hence for any modification in the existing project to be undertaken it has to be economically sound and viable. Therefore, this study also seeks to establish the economic viability of the modification work proposed. A comparison of CCPP performance parameters for both with and without GT inlet air cooling system is illustrated in the Table 5.1.

Equipment name	**Parameters without TIAC**	**Parameters with TIAC**	**Change in parameters**
Gas turbine Gross power output (MW)	222.44	240.555	18.12
Steam turbine Gross power output(MW)	129.072	131.683	2.611
Plant total power output at generator terminal(MW)	351.516	372.240	20.724
Total auxiliaries power consumption (MW)	9.116	9.238	0.122
Plant net power output(MW)	342.40	362.989	20.589
Plant net LHV heat rate(kJ/kWh)	6559	6493	Improved
Plant net LHV electric efficiency (%)	54.88	55.44	0.56
Heat rate per MW (kJ/kWh)	18.175	17.011	1.164
Fuel mass flow rate (t/h)	45.74	48	2.26
Cooling water pump flow (t/h)	19136	20124	988

Table 5.1. Comparison of CCCP output parameters with and without



GT inlet air cooling system

Fig.5.1. Comparison of plant power output and heat rate with/without chiller.

The total net power output and electrical efficiency are increased by about 20.59 MW and 0.56% point respectively. The improvement of heat rate per MW is 1.164 kJ/kWh; same is represented in the graphical form as shown in Fig.5.1

5.2 Economical Analysis of Inlet Air Cooling System

The estimation of the total investment cost of TIAC system package and its payback period is required to verify whether the proposed project is financially viable.

The capital investment cost consists of cost incurred for procurement, erection and site testing/commissioning. The Operating cost includes operating and maintenance of the system.

Payback period is the one of the simplest investment appraisal techniques. This is defined as the time in which the initial cash outflow of an investment is expected to be recovered from the cash inflows generated by the investment.

It is estimated that the total project cost for retrofitting/installing the TIAC system in the plant is about Rs.397.48 Lakhs. This is inclusive of Interest during Construction (IDC) and Financing Cost (FC).

Net power generation has been calculated, by considering that the plant will operate with the TIAC for 4 hours operation during 4 peak summer months with a plant load factor (PLF) of 80% and additional cost obtained due to selling of additional power generated per annum was estimated to be about Rs.252.99 Lakhs by considering electricity selling price of about Rs.3.2 per kW.

Additional fuel consumption per annum due to modification is estimated to be 1225762.7 scm/year. Annual fuel cost is calculated as Rs.103.88 Lakhs by considering fuel cost @ Rs.8.475 / scm. Also other fixed charges per annum including 16% ROE is estimated about Rs.64.48 Lakhs. Hence, total fixed and running charges per annum is about Rs.168.36 Lakhs.

Net profit per annum due to modification after subtracting the total fixed and running charges from the additional cost obtained from additional power generated is about Rs.84.63 Lakhs.

The payback period is calculated as shown in below Table.5.2.

Plant operating years	**Net profit at the end of each year (Rs. Lakhs)**	**Total project cost value at the end of each year (Rs. Lakhs)**
0	0	397.49
1	84.63	312.86
2	169.26	228.23
3	253.88	143.60
4	338.51	58.98
4 years and 9 months	401.98	-4.49

Table 5.2 Calculation of payback period.

The payback period estimated is about 4 years and 9 months for total capital investment of Rs.397.49 Lakhs, considering that the proposed TIAC system will operate only for 4 hours at peak summer months. The same will be reduced in case the system is operated more than the considered operating hours.

6.0. CONCLUSION

The performance of a gas turbine as well as the combined cycle power plant is mainly depends on the inlet air temperature. Reduction in the temperature of air will increase the power output due to the increase in density and mass flow rate of air. By applying the TIAC system (with hot water based VAM), a decrease of about 8°C inlet air temperature, will increases the net power output by approximately 20.589 MW. Also, the efficiency is increased about 0.56% point and heat rate per MW is improved by about 1.164 kJ/kWh. The total investment cost for this will be Rs. 398 Lakh with a payback period of 4.9 years.

7.0. REFERENCES

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