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THERMODYNAMIC SIMULATION AND EFFICIENCY ANALYSIS OF THE COMBINED HEAT AND POWER PLANT

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ABSTRACT

This investigation presents a thermodynamic modeling and efficiency analysis to optimization study of a combined cycle power plant and a combined heat and power system to survey all the parameter that affect efficiency and performance of the plant, the selected variables for optimization study are the ambient parameter and the mass flow and temperature of exhaust of gas turbine and the steam living the boiler and the gas flue temperature at exit of HRSG's stack and the type of cooling and condenser heat rejection and fuel consumption in duct burner and combustion chamber of gas turbine and power output and efficiency of steam turbine and gas turbine and plant to improving the efficiency, net output, heat rate of the plant.

INTRODUCTION

Improving the efficiency of the combined cycle has been the subject of many investigations, the majority of studies have been used improve the efficiency of the gas cycle or steam cycle to enhance the efficiency of the combined cycle. The main purpose of the present study is to identify different technical parameters that affect the combined heat and power plant efficiency and heat rate. The thermodynamic behavior of total component of CHP plant versus the plant criteria, gas turbine input, steam turbine and heat recovery steam generator input have been studied, the graphic result and thermodynamic analysis presented. This cogeneration system had been designed under Iran summer climate conditions.

NOMENCLATURE

CCPP	*[-]*	*combined cycle power plant*
CHP	*[-]*	*combined heat and power*
GT	*[-]*	*Gas Turbine*
ST	*[-]*	*Steam Turbine*
HRSG	*[-]*	*heat recovery steam generator*
HP	*[bar]*	*high pressure*
LP	*[bar]*	*low pressure*
η	*[%]*	*efficiency*
P	*[Wat]*	*power*
Q	*[J]*	*heat*

THERMODYNAMIC SIMULATION

The main challenge in designing a combined-cycle plant with a given gas turbine is how to transfer gas turbine exhaust heat to the water/steam cycle to achieve optimum steam turbine output. The focus is on the HRSG in which the heat transfer between the gas cycle and water/steam cycle takes place.

Simulation of the plant has been done by THERMOFLOW (version 17) software which the relevant input data have been extracted from following sources:

- Gas turbine's Performance parameters, Siemens SGT5-2000E (KWUV94.2), of a capacity 164 MW at ISO condition, MAPNA Company applied in this project.
- Detail design data of dual pressure heat recovery steam generation with natural circulation (HRSG), MAPNABOILER Company designed according the client demand.

- Steam turbine's performance parameter, 159 MW, turbine generator unit, MAPNA Company applied in this project.

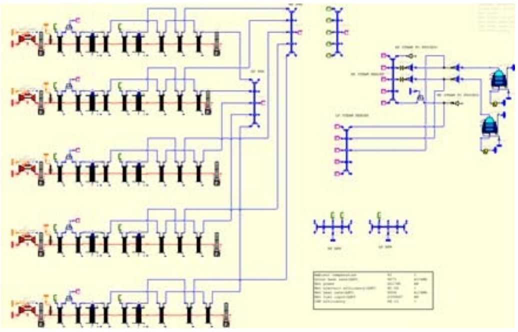

Figure 1 Combined heat and power plant (5 GT+5HRSG+2ST+2ONCE THROUGH COOLING) simulation in THERMOFLEX as one module of THERMOFLOW

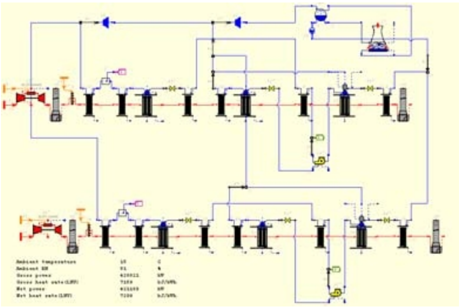

Figure 1 Combined cycle power plant (2GT+2HRSG+1ST+Heller cooling) simulation in THERMOFLEX as one module of THERMOFLOW

CASE STUDY

The present simulation has been applied in possible CCPP or CHP of MAPNA CO. The configuration of the CCPP plant is 2GT+2HRSG+1ST+ 1 Heller cooling, with net power output 906 MW, and the CHP has been designed with 5GT+5HRSG+ 2ST+ 2 once through cooling. The demand of this plant is electrical power and superheated steam for process in two pressures HP and LP. One block combined cycle which consisting of two Gas turbine sets & HRSG & one Steam Turbine is about 470 MW at ISO condition (15°C, 60% relative humidity and 1013 mbar pressure) with standard gas fuel (100% methane) consumption. The V94.2 gas turbine is single casing gas turbine of heavy duty design with common shaft for compressor and turbine and a nominal rating of approx.162 MW (ISO condition, 100% Methane gas fuel consumption). HRSG and their auxiliary equipments will be considered for combined cycle, designed and built by MAPNA CO. these HRSG will be of horizontal type with natural circulation and designed for fired conditions. each HRSG in gas flow direction has HP,LP Superheater, HP,LP Evaporator Banks, HP Economizer steam prevention design, Deaerator Evaporator Banks and Condensate pre-heater (CPH). In order to ensure natural circulation and allowing steam-water separation, each pressure level of HRSG has own steam drum. Evaporator will be made of vertical tubes, top header discharges into the steam drum via riser tubes and bottom header is fed from down comers, ensuring natural circulation and drain ability. The superheater and economizer tubes are arranged in vertical elements, finned, and are connected to horizontal headers. Feed water is passed through economizer and discharged to the boiler steam drum through a perforated distribution pipe in the lower section of the drum. A spray-type de superheater inter-stage is used to keep the superheated steam temperature in the required range. The E-type, HP/LP Steam turbine consists of single cylinder straight flow, which comprises a low pressure and a high pressure section. In the HP and LP section of the turbine the energy of the turbine the energy of the steam is converted to mechanical work. The total enthalpy drop across the steam turbine comprises two sections of expansion. The condensing turbine is an axial flow turbine with two main steam inlets at the HP part and one inlet for the induction steam. Thermal cycle system start from condenser hot-well and is returned to thermal cycle. The condensate water is fed by condensate pump to the condensate pre-heater, where it is heated up to CPH outlet temperature and then delivered to the feed water storage tank via integral deaerator when GT is gas fired. The CPH is bypassed when GT is gas oil fired and when CPH inlet temperature is cold to avoid water dew point at out-surface of CPH tube. The feed water storage section increases water temperature from thermal energy contained in the GT exhaust gas. The water is fed from feed water storage tank through down comers to the inlet header of deaerator evaporator. The purpose of the HP feed water system is to maintain the required water level in the HP drum as well as to supply spray water for HP super heater Attemperator by supply feed water from feed water storage tank to the HP economizer inlet header. Each boiler HP/LP feed water pump draws water from the feed water storage tank by means of common suction piping. The boiler feed water pumps discharge in to common HP feed water header. The purpose of the LP feed water system is to supply feed water from storage tank to the LP drum to maintain the required water level in the LP drum. One of other system is HP/ LP by-pass system, provided for each HRSG to regulate the steam flow to the steam turbine according to the required load in comparison with the steam quantity generated from the boilers. It is used during start up and shut down of the power plant, at load reduction or after turbine trip and discharge the excess steam via the HP/LP bypass steam valves to the condenser. Both designed for the 100% mass flow of relevant boiler at design conditions. This combined heat and power block consist of 5 GTs and HRSGs and 2 steam turbines and 2 once through cooling. Thermal cycle of the combined heat and power is nearly as same as combined cycle, except the process steam consumption and the number of GT and HRSG and Steam turbine. Steam production from 5 HRSG's collected in HP and LP steam header, HP header outlet is divided to three consumptions, such as steam turbine and process and let down station (HP steam throttling through the control valve and is decreased temperature by spray water Attemperator to produce LP steam process demand). LP header outlet has two consumers such as steam turbine and process demand.

RESULT AND DISCUSSION

The general definition of the electrical efficiency of combined cycle plant and combined heat and power system are:

$$\boldsymbol{\eta_{cc}} = \frac{P_{GT}+P_{ST}}{Q_{GT}+Q_{SF}} \qquad (1)$$

$$\boldsymbol{\eta_{CHP}} = \frac{P_{GT}+P_{ST}+Q_{Process}}{Q_{GT}+Q_{SF}} \qquad (2)$$

According the equations 1& 2 improving the efficiency of the plant is dependent of net power of GT and ST and heat of process and fuel consumption in GT and HRSG.

GT power will differ from plant to plant depending on ambient parameter. ST power is function of expansion work of steam flow which producing by HRSG and ST back pressure or ambient parameter effect on condenser design. Fuel consumption in HRSG are applied to compensate the thermal input in GT flue gas and this is influence of ambient and GT response to plant variation. Steam production has different consideration which studied in HRSG input design parameter such as pinch point and approach sub cooling

- **Ambient parameter (Temperature, Altitude, Relative Humidity)**

In this section the effect of ambient parameter in power output of plant is presented. Improving the GT efficiency is helpful only if it does not cause too great a drop in efficiency of steam process. And steam production in HRSG is function of mass flow and temperature of GT exhaust flue gas and those are more sensitive to ambient parameter, this performance is common in CCPP and CHP.

In this section the effect of temperature, site altitude and relative humidity variation on the efficiency of GT and ST and HRSG are studied .the majority of dependence is related to GT performance, then thermal input to HRSG, therefore steam production. Volumetric input air flow at different condition is approximately constant and density of air is variable. The results related to effect of ambient parameter such as temperature, altitude, relative humidity, variation are presented in the below figure:

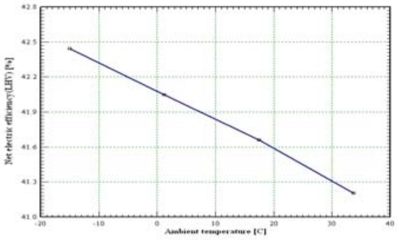

Figure 3 Net electric efficiency of the plant behavior in different ambient temperature.

Whereas the power outputs of GT and LP steam are fallen the electrical efficiency of plant is too (Fig.3). The efficiency of a cogeneration plant that produces useful heat as well as electric power, CHP efficiency improved (Fig.4).

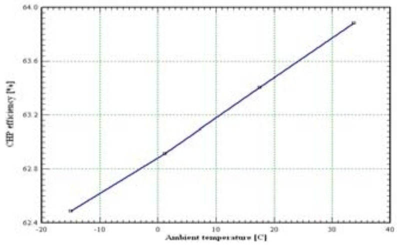

Figure 4 Combined heat and power efficiency of the plant behavior in different ambient temperature.

By increasing the ambient temperature the density and mass flow rate at inlet of GT reduce but the exhaust temperature increases this effects result to decrease of power output of GT (Fig.5) and then can be coupled for HRSG high pressure heating surface and steam production so that flue gas with lower mass flow against high enthalpy and temperature have less heat transfer across the LP super heater to HP super heater and steam production in HP section of HRSG improved but the ratio of temperature and mass flow at LP section to ambient temperature variation is nearly constant, therefore decline of mass flow of steam at ST inlet not only yield to HP ST expansion power output increment (Fig.6) but also LP ST expansion work is approximately decrease (Fig.7).

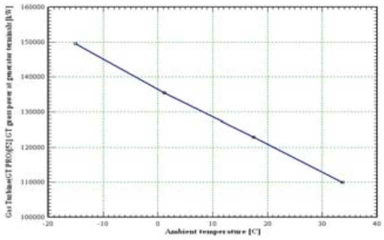

Figure5 GT power output behavior in different ambient temperature in combined heat and power plant.

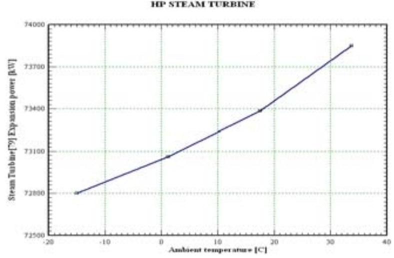

Figure 6 HP Steam expansion power output in different ambient temperature in combined heat and power plant.

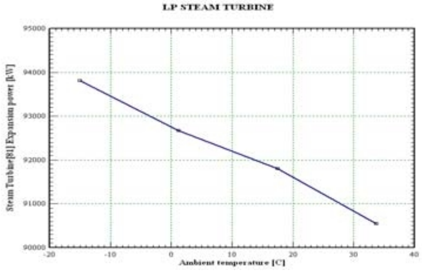

Figure 7 LP Steam expansion power output in different ambient temperature in combined heat and power plant.

spray condenser mass flow in Heller cooling type and condenser heat load reducing. A change in ambient temperature affects the amount of heat to be removed in condenser because the change in steam mass flow. The lower the live steam mass flow the less heat must be removed in the condenser. The following will bring economical advantages such as a smaller condenser and reduction of the cooling water requirement for spray. Increasing the site altitude has same effect such as ambient with this CHP Efficiency difference that result of GT inlet air flow temperature cooled in high altitude. Low inlet air mass flow coupled with low temperature has strong effect on the GT Exhaust flue gas. Thermal input and steam production in HRSG and the rate of steam production and power output to fuel input in the plant are fallen. (Fig.8 &9)

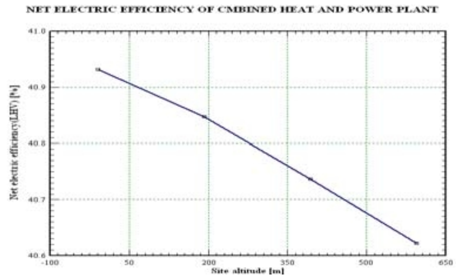

Figure 8 Net electric efficiency of the plant behavior in different site altitude.

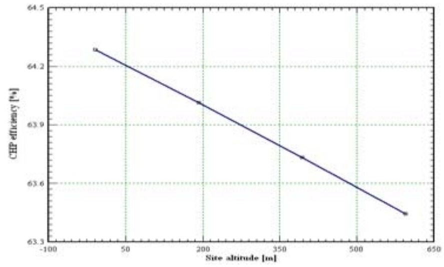

Figure 9 Combined heat and power efficiency of the plant behavior in different site altitude.

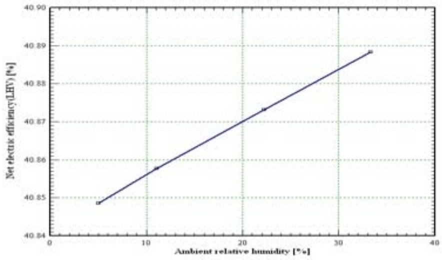

Figure 10 Net electric efficiency of the plant behavior in different relative humidity.

Higher inlet air humidity decrease the air density so by considering constant volumetric flow in GT the mass flow rate will be decreased consequently the power output and electric efficiency of plant. In this case because of high humidity the specific heat of GT

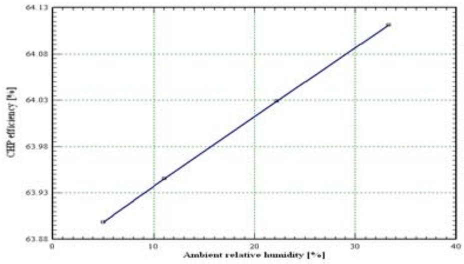

Figure 11 Combined heat and power efficiency of the plant behavior in different relative humidity.

exhaust gas will be increase which improved the heat transfer in HRSG so steam production grows up and cause to improve steam turbine expansion work and process steam demand and CHP efficiency(Fig.10 & 11).

- **HRSG DESIGN INPUT PARAMETERS**

APPROACH SUBCOOLINGTEMPERATURE is the difference between the saturation temperature and the evaporation inlet water temperature. High approach temperature put more duty in the drum section which increases the total heating surface area and cost of HRSG. Low approach may result in steaming economizer at low load. Boiler feed water temperature is depend to ambient condition of plant, in low temperature an exchanger is used to preheat the water before enters the deaerator, thus lowering the deaerator steam requirements and affect the efficiency of boiler system (Fig.12).

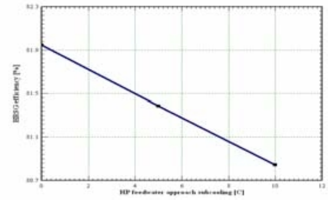

Figure 12 HRSG Eff. By increasing the approach sub cooling

PINCH POINT is the difference between the flue gas temperature leaving the evaporator section and the saturation temperature corresponding to the steam pressure in evaporator. Lowering the pinch point not only increases the amount of heat recovered but also increase the surface requirement (Fig.13). From thermodynamic view point decreasing the pinch point and approach temperature increase the boiler efficiency but because of some problems as it mentioned above the pinch point and approach point are limited.

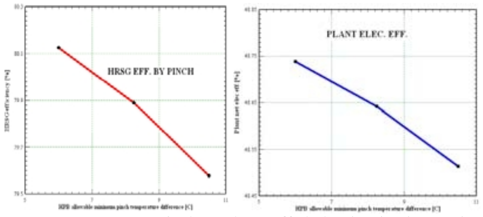

Figure 13 HRSG and plant elec. Eff. behavior by increasing the pinch point

WITH SUPPLEMANTARY FIRING the efficiency of the boiler increases while plant's efficiency decreases. The reason is that with the same flue gas exhaust of GT, entering burner more fuel is being fired thus reducing the excess air leaving the stack; also, with an increase in inlet gas temperature the exit gas temperature from HRSG decreases, this is due to the significantly larger ratio of water to gas flow in fired mode compared to the ratio in the unfired mode. The flue gas remains nearly constant, while the steam production and the water flowing through the economizer increases, depending on the extent of firing. As seen from the modeling result with additional fuel input heat rate of the plant are more increases than ST power output then the efficiency of the total plant decreases (Fig. 14).

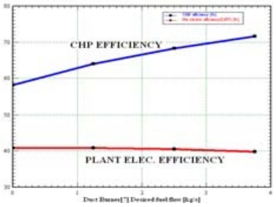

Figure 14 CHP and plant elec. Eff. With firing in HRSG

Despite the fact that the majority of the HRSGs are unfired, there are occasional applications where a limited amount of supplementary firing is needed.

The importance of supplementary firing in HRSG s for power generation alone is diminishing. This is mainly caused by two facts:

- Modern gas turbines have exhaust-gas temperature closer to the maximum allowable HRSG inlet gas temperature reducing the effect of any supplementary firing.
- Supplementary firing behind a modern gas turbine gas turbine results in an efficiency decreases for the combined-cycle. With older gas turbine models the efficiency was more or less constant. Supplementary firing is most often applied in combined-cycle cogeneration plants where the amounts of process steam must be varied independently of the electric power generated. In this case supplementary firing controls the amounts of process steam generated and also the most important benefit of duct burner firing is increasing the HRSG and Cogeneration plant efficiency.

Actually the efficiency of fuel firing in duct burner for steam generation is nearly 100% because in case of supplementary firing the HRSG exhaust gas temperature is decreased comparing to the HRSG unfired case. So it is better to burn the fuel in HRSG for steam generation capering to burn the fuel in conventional boiler which it's maximum efficiency is about 90%. The Result of modeling is confirmation of above mentioned. Stack exit temperature by fuel firing decline demonstrates that thermal energy in GT exhaust more recovered and steam production grows up thus to satisfy the process demand with desire temperature de super heaters apply more feedwater mass flow to control these amount of steam flow at existence of evaporators(Fig.15).

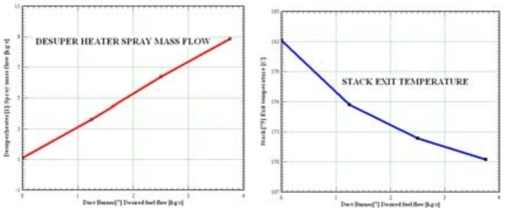

Figure 15 de super heater spray mass & Stack exit temperature flow with firing

- **COOLING WATER TEMPERATURE(ST BACK PRESSURE)**

A change in cooling water temperature affects the volume flow of the steam turbine exhaust steam when the cooling water temperature falls so the benefit due to a better condenser vacuum is reduced. If the cooling water temperature is higher, the condenser pressure increases, thereby reducing the steam turbine output.ST back pressure directly depends on cooling tower temperature which it limited by ambient temperature and cost impact due to increasing heating surface but decreasing back pressure increase the ST pressure ratio which finally improve the combined cycle efficiency.(Fig.16)

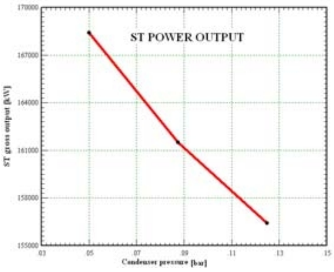

Figure 16 ST Power output by increasing the condenser pressure

CONCLUSION:

- The site conditions have an influence to the gas turbine performance and also the HRSG output is affected. In cold areas or sea levels the gas turbines and HRSG produce more power when compared with the units operating in hot environments or higher altitude. Also at higher altitudes, because of higher pressure drop in HRSG for the same amount of gas flow the capacities are reduced.
- Supplementary firing is an efficient way to increase the steam generation in HRSGs normally the heat input through the burner is fully recovered in the HRSG. But in addition, more heat from the gas turbine exhaust gas will also be recovered. So the net effect of firing is to make the HRSG more efficient than the unfired case. This is the reason for the apparent burner efficiency of greater than 100% or more heat extraction than the amount put in through the burner. Typically, HRSGs in combined cycle plants are unfired and those in cogeneration plants are fired.
- The pinch point and the approach point have a big influence to the steam flow, if it is assumed that the other parameters are fixed. With a lower pinch point more steam is produced at that pressure stage. If the approach point is decreased, less steam must be condensed to preheat the economizer outlet water to saturated temperature .To decrease the pinch point it is normally necessary to increase the transferred heating power. That means often to increase the heating surface or the gas side pressure drop. So there is a search for the optimum with higher efficiency and lower costs.
- The minimum of the exergy losses in the HRSG is, if the heating of the working fluid (in this case Water) has a minimum temperature difference to the cooling of the other (hot) fluid (flue gas of the gas turbine). There are two main ways to decrease the temperature differences between flue gas and water: 1. Multiple pressure stages 2. Once through boiler. Which for multiple pressure it shall be considered at least two level pressure one of them high pressure and another one very low pressure.

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