Abstract-- Thermodynamic model of wet compression in a combined cycle system is established in this paper. The objective of this paper is to improve the performance of combined cycle system by injecting suitable quantity of water into the compressor. A Microsoft excel based tool is developed to do the thermodynamic sensitivity analysis for the system. The results show that the pressure ratio, water injection quantity, ambient temperature etc strongly influence the overall performance.

Keywords: combined cycle system, wet compression, gas turbine

I. INTRODUCTION

Combined cycle power plants have both gas and steam turbines based on more than one thermodynamic cycle – Brayton (gas) and Rankine (steam). The gas turbine cycle in a combined cycle power plant, first produces power and the waste heat from the exhaust gas is used to make steam to generate additional power through a steam turbine, which enhances the efficiency of electricity generation. Compare to other power plants the advantages of combined cycle plant are high flexibility, quick part-load starting, suitability for both base-load and cyclic operation, and a high efficiency over a wide range of loads. In this paper the objective is to improve the net work done and efficiency of the combined cycle system by wet compression. Wet compression is a process in which water droplets are injected into the air in the form of fine water droplets (spray form). As the water droplets evaporate in the front stages of the compressor, it reduces the air temperature and therefore reduces the amount of compressor work [1].

II. SYSTEM ANALYSIS

A. Overview

The schematic diagram of combined cycle system with wet compression is shown in Figure 1.

First, in the wet compression system air is cooled by introducing water into the air in the form of fine water droplets (spray form). The reduction in the air temperature is limited by the ability of air to absorb water. After that air water mixture is compressed into the compressor. Now the compressed air is sent to the combustor where there is addition of fuel takes place. Due to combustion, hot gases generated into the combustor runs the gas turbine. In HRSG the incoming feed water is converted into steam by absorbing heat from the exhaust gas that steam runs the steam turbine.

B. Assumptions

The following assumptions are made to simplify the calculations however they can be refined to reach more real solutions. The main assumptions are

- Natural gas is used as a fuel (CV=43000 KJ/Kg K)
- Working fluid is assumed to be air as an ideal gas
- Air water mixture flow rate at inlet is taken 1Kg/s
- Water amount is between 0-27% of air mass flow
- Water and air inlet temperature and pressure is atmospheric (298 K, 1atm)
- Compression and expansion processes in compressor and turbine are assumed to be adiabatic considering compressor and turbine efficiency varying with pressure ratio [4]. The efficiency of steam turbine assumed as 82%
- Combustion chamber pressure loss is negligible
- Steam injection temperature 700 K and pressure 40 bar
- Pressure ratio 10 bar where ever applicable
- Fuel injection rate 3% of air mass flow rate
- Feed water temperature in HRSG is taken as 300 K at condenser pressure of 0.04 bar
- Pump work is neglected during performance calculations

C. Thermodynamic calculations

The performance analysis of combined cycle system is based on Steady Flow Energy Equation (SFEE).
**Process 1-2 (Adiabatic compression)**
Compressor work
\[ W_C = m \cdot C_{pc} \cdot (T_2 - T_1) / \eta_C \]

**Process 2-3 (Constant pressure heat addition)**
Energy equation
\[ (m+f) \cdot C_{pp} \cdot T_3 = f \cdot CV + m \cdot C_{pc} \cdot T_2 \]

**Process 3-4 and a-b (Adiabatic expansion)**
Work done by the Turbine,
\[ W_{GT} = (m+f) \cdot C_{pp} \cdot (T_3 - T_4) \cdot \eta_{GT} \]
\[ W_{ST} = y \cdot (h_a - h_b) \cdot \eta_{ST} \]

**Process 4-5- (Constant pressure heat rejection in HRSG)**
Energy equation-
\[ (m+f) \cdot C_{pp} \cdot (T_4 - T_5) = y \cdot (h_a - h_b) \]

**Overall Performance**
Net work, \( W_{net} = W_{GT} - W_C + W_{ST} \)
Thermal Efficiency:
\[ \eta_{th} = W_{net} / Q_1, \text{ Heat addition, } Q_1 = f \cdot CV \]
Specific fuel consumption (sfc) = \( 3600 \cdot f / W_{net} \)
Heat rate = \( 3600 / \eta_{th} \)

III. RESULTS & DISCUSSIONS
Performance analysis of a combined cycle system links the
thermodynamic behavior among its subsystem and establishes the mathematical relationship to arrive on various performance or cycle parameters like max cycle temperature, net work, efficiency etc. The different combinations of water injection, pressure ratio, compressor inlet temperature, combustor exit temperature and several such parameters are considered as variable. Some of the important observations are highlighted in this paper and detailed as below.

Figure 2 shows effect of water injection on compressor work at different pressure ratio. By increasing the pressure ratio compressor work is also increasing. Also by increasing the water injection into the compressor at constant pressure ratio, the compressor work is reducing. In this paper our aim is to reduce compressor work so that net work output will increase. With the help of graph it can be seen that compressor work is maximum at zero water injection, if the water injection exceeds 0.24 Kg/s we will get negative compressor work. From the references [1] [6] [10] and [18] the recommended water injection quantity is 1-3%.

Figure 3 shows effect of water injection on combustor exit temperature at different fuel injection flow rate. Turbine inlet temperature increases when fuel injection increases but it decreases with the increase in water injection. When fuel addition is more, more heat is generated into the combustion chamber; this heat raises the temperature of gas which comes out of the combustor.

Figure 4 shows effect of pressure ratio on gas turbine work at different fuel injection. With the increase in pressure ratio turbine work is also increasing. It has been also seen that with the increase in fuel injection into the combustor at constant pressure ratio the work done by the turbine has improved. From the figure, the work done by the turbine is highest at maximum pressure ratio and maximum fuel injection.

Figure 5 shows effect of steam turbine efficiency on steam turbine work at different steam injection. With the increase in steam turbine efficiency turbine work is also increasing. It has been also seen that with the increase in steam injection into the turbine, work done by the turbine has improved. From the figure, the work done by the turbine is highest at maximum turbine efficiency and maximum steam injection.

Figure 6 shows effect of steam injection on net work output at different water injection. Net work done is continuously increasing with the increase in water and steam injection, the relationship is linear. Work done is highest at highest steam injection and highest water injection.

Figure 7 shows effect of pressure ratio on thermal efficiency with different water injection and constant steam injection of 20% of air mass flow rate. Thermal efficiency increases with
the increase in pressure ratio and by increasing the water injection into the compressor at constant steam injection. Thermal efficiency is highest at maximum pressure ratio and maximum water injection.

Figure 8 shows the effect of compressor inlet temperature on specific fuel consumption at different fuel injection. In case of combined cycle it can be seen that specific fuel consumption increase is very less with the increase in inlet temperature it means that the effect of inlet temperature increase is very less but sfc improves with the increase in fuel consumption.

Figure 9 shows the effect of compressor inlet temperature on heat rate at different fuel injection. In case of combined cycle it can be seen from the figure that when the value of fuel injection is minimum i.e. 0.01 Kg/s the heat rate is minimum and suddenly there is much improvement in heat rate value when there is slight increase in fuel injection. Also when fuel injection value crosses 0.025 Kg/s there is not much improvement in heat rate value.

IV. CONCLUSION

The system formulation and computer implementation described in the preceding section repertoire the performance calculations of the combined cycle system. This section summarizes the sensitivity of performance parameters of the major modules of combined cycle system. A design methodology has been developed for parametric study and performance evaluation of a combined cycle system which shows that pressure ratio, inlet air temperature, water injection etc played a very vital role on overall performance of gas turbine system. MS excel based tool is developed to carry out the sensitivity studies of performance parameters.

V. APPENDIX

The appendix provides the performance charts of cogeneration system with wet compression and steam injection.

![Figure 2 Effect of water injection on compressor work at different pressure ratio](image)

![Figure 3 Effect of fuel injection on turbine inlet temperature](image)
Figure 3 Effect of fuel injection on turbine inlet temperature at different water injection

Figure 4 Effect of pressure ratio on turbine work at different fuel injection

Figure 5 Effect of steam turbine efficiency on steam turbine work at different steam injection

Figure 6 Effect of steam injection on net work output at different water injection
Figure 7 Effect of pressure ratio on thermal efficiency with different water injection

Figure 8 Effect of compressor inlet temperature on sfc at different fuel injection

Figure 9 Effect of compressor inlet temperature on heat rate at different fuel injection

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NOMENCLATURE

\[ \eta_c = \text{Thermal efficiency of compressor} \]
\[ \eta_{GT} = \text{Thermal efficiency of turbine} \]
\[ \eta_{ST} = \text{Thermal efficiency of turbine} \]
\[ \eta_{th} = \text{Overall thermal efficiency of cycle} \]
\[ C_{pc} = \text{Specific heat of mixture (KJ/Kg K)} \]
\[ C_{ps} = \text{Specific heat of steam (KJ/Kg K)} \]
\[ C_{pp} = \text{Specific heat of products of combustion (KJ/Kg K)} \]
\[ C_{VT} = \text{Calorific value of fuel (KJ/Kg)} \]
\[ f = \text{Mass flow rate of fuel supplied (kg/s)} \]
\[ h_s = \text{Enthalpy of steam (KJ/Kg)} \]
\[ h_p = \text{Enthalpy of water (KJ/Kg)} \]
\[ m = \text{Mass flow rate of mixture (air + water) (Kg/s)} \]
\[ Q_1 = \text{Heat addition (KW)} \]
\[ T_1 = \text{Compressor inlet temperature (K)} \]
\[ T_2 = \text{Compressor exit temperature (K)} \]
\[ T_3 = \text{Combustor exit temperature (K)} \]
\[ T_4 = \text{Turbine exit temperature (K)} \]
\[ T_6 = \text{Feed water inlet temperature in (K)} \]
\[ T_7 = \text{HRSG exit temperature (K)} \]
\[ W_c = \text{Compressor work (KW)} \]
\[ W_{GT} = \text{Gas turbine work (KW)} \]
\[ W_{net} = \text{Net work done (KW)} \]
\[ W_{ST} = \text{Gas turbine work (KW)} \]
\[ x = \text{Mass flow rate of water injection (Kg/s)} \]
\[ y = \text{Mass flow rate of steam injection (kg/s)} \]

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