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Modelling, Simulation and Optimization of Thermal Systems in Supercritical Thermal Power Plant Cycle

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ABSTRACT

Modelling, Simulations and optimization are extensively used in thermal power plant industries to evaluate the dynamic output responses of various thermal systems. The choice of optimal simulation parameters can lead to improve operation and time, but configuring them to produce maximum power output is a challenging problem. In power plants, there are so many parameters like steam pressure, temperature and steam extraction pressures from various high, intermediate and low pressure steam turbines (HPT and IPT+LPT) affects the efficiency of a plant and need optimum values in order to get maximum power output. In this process Cycle Tempo 5.0 simulation software was used to analyse the efficiency of supercritical thermal power plant cycle with a capacity of 660 MWe with and without optimization. Quasi-Newton optimization method is applied that would offer the maximum efficiency of a power plant cycle for certain standard following input parameters of industrial power plant. Eight stages of regenerative feed water heater arrangement with and without flue gas for heat recovery circuit are considered for the analysis and the results were compared. The obtained values are in good agreement with industrial power sector results. The considered power plant is also analysed at various environmental perspectives like atmospheric temperature variations.

Keywords: Quasi-Newton Optimization, Supercritical Cycle (SC), Lower heating value of coal (LHV) Economizer (ECON).

1 INTRODUCTION

There is no distinction between gas and liquid phase, the mass density of the two phases is the same when the water is heated at above the critical pressure (>221.2bar), and its temperature is more than 374.5 ^{0}C. Properties of the water in the supercritical conditions change from liquid to gas within a fraction of seconds as heat is applied. When the steam pressure and temperatures are at 250 bar and 600 ^{0}C, the capacity of power plant is above 500 MWe are called supercritical thermal power plants.

Patric et al. [1] have compared calculation approaches such as Quasi-Newton Optimization and Derivative Free Optimization (DFO) subroutines for simple water steam cycle with single open feed water heater and with 8 regenerative stages for a plant capacity of 660 MW. They have reported the thermal efficiency decreases as the bled steam pressure increases and also highlighted the time taken for simulation. Yu et al. [4] have developed new heat transfer correlation of water at supercritical pressure based on existing test data using genetic algorithms. Alobaid et al. [5] have done analysis on dynamic modelling and numerical simulation of a triple pressure supercritical once-through heat recovery steam generator at 250 bar pressure in the high pressure circuit during load changes using advanced process simulation software (APROS). Sanpasertparnich et al. [6] have studied optimal design parameters that would offer the maximum power plant efficiency of both subcritical and supercritical operating conditions for a capacity of 350 MW to 450 MW using rank correlation coefficient and Monte Carlo simulation approaches. Sergio et al. [7] have simulated supercritical unit with plastic heat recovery heat exchangers instead of metallic heat exchangers which were used in old power plants for the optimization of boiler cold end integration with the steam cycle to recover the waste flue gas energy. Elsner et al. [9] have made analysis on the optimization of supercritical coal fired power plant for two high pressure feed water heaters with IPSEpro connected with MATLAB using PSExcel, a special macro file, which allows for efficient data exchange in both directions. Wang et al. [10] have simulated the performance of a supercritical power plant with eight stages of regenerative feed water heaters to a capacity of 670 MW using Ebsilon software. They have analysed the cycle with endogenous / exogenous exergy destruction, avoidable/unavoidable exergy destruction in various components of the cycle. Siva Reddy et al. [11] have carried out work on energetic and exergetic analysis of coal-fired supercritical thermal power plant with nine feed water heaters using engineering equation solver (EES).They have reported the overall energetic and exergetic efficiency of coal-fired supercritical thermal power plant are found to be 43.48 and 42.89 %, respectively.

To the authors' knowledge from the above studies on power plant cycles review, it is observed that most of the researchers have made power plant component analysis using different software tools only for a particular power plant capacity. Some of the authors have carried work on variables influencing on a particular power plant capacity at different atmospheric conditions. Some of the research scholars highlighted analysis only on a single component i.e. either on boiler/turbine/condenser and feed water heaters in the power plants. There is a dearth of literature and some gap on the number of iterations required to obtain the simulations before and after optimization of conventional power plant cycle and also it is also compared with flue gas heat recovery heat exchanger devices for the same power plant configuration with a capacity of 660 MWe. Therefore an attempt is made to solve the problem on simulation of thermal systems to obtain the optimum steam extraction pressure of supercritical thermal power plant using Cycle Tempo 5.0 simulation software. SIPAT Stage 1 power plant steam input parameters are considered in the simulation analysis.

2 POWER PLANT CYCLE DESCRIPTION

The schematic layout for supercritical power plant cycle with a capacity of 660 MWe connected with eight regenerative feed water heaters are shown in figure 1. Coal with lower heating value is 28938 kJ/Kg considered in the analysis. The steam generator efficiency is 92 %. The feedwater from the regeneration system enters in to steam generator. The steam gets heated to 574 ^{0}C in steam generator and enters into HPT. After expansion to low pressure in HPT, the steam goes to reheating section and gets reheated to 538 ^{0}C in reheater, mostly preferred in power plants. The reheated steam enters in to (IPT+LPT). The main steam gets expanded through stages of HPT and (IPT+LPT) to generate the electricity. Then, the final exhausted steam is condensed in a condenser.

To increase the thermal efficiency of the cycle, parts of the expanded steam is extracted at different locations of the turbine to heat the feedwater in regeneration system, including four low-pressure feed water heaters (LPFWH1-LPFWH4); one open feed water heater (OFWH 5) also called Deaerator (DEA) and three high-pressure feed water heaters (HPFWH1-HPFWH3). To meet the large amount of input power required by the boiler feed pump (BFP), one feed pump turbine (FPT) is connected to BFP. To carry out the work for supercritical power plant cycle, some of the assumptions considered for simulation process are taken from the literatures and from SIPAT Thermal Power Station plant capacity of 660 MWe are shown in table 1.

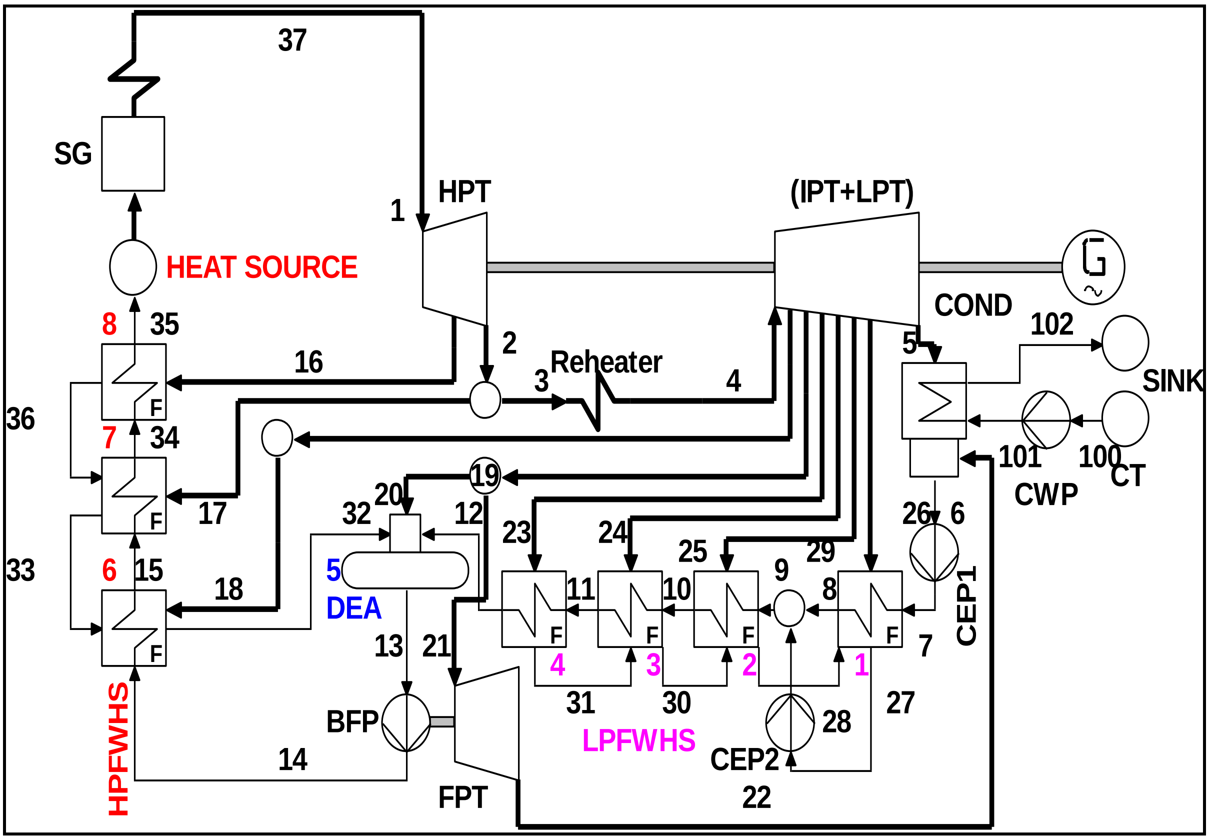

Figure 1: Supercritical Thermal Power Plant capacity of 660 MWe without flue gas heat recovery circuit

The schematic layout for supercritical power plant cycle with a capacity of 660 MWe is connected with eight regenerative feed water heaters considering the flue gas heat recovery circuit shown in figure 2. Air along with coal is entered in to the combustor**.** The generated flue gases pass through different heat recovery heat exchanger devices via evaporator, 3 superheater sections, 2 reheater sections, economiser, air preheater, induced draft fan and finally goes out through chimney. The steam generator efficiency is 92 %. The feedwater from the regeneration system enters in to steam generator. The steam gets heated to 574 ^{0}C in evaporator (EVAP) and enters into HPT through various superheater sections (SHs). Three superheaters (one radiative and two convective) are arranged along the length of flue gas path Steam after expansion in HPT, the steam goes to reheating sections through combustible (COMB) flue gases and gets reheated to 538 ^{0}C in reheater, mostly preferred in thermal power plants. Heat recovery heat exchangers devices are provided along the flue gas lines. Air is preheated in air preheater (APH). Saturated feed water also gains heat through flue gas arrangement via economiser (ECON).The reheated steam enters to (IPT+LPT). The main steam gets expanded through stages of HPT and (IPT+LPT) to generate the electricity. To increase the thermal efficiency of the cycle, parts of the expanded steam is extracted at different locations of the turbine to heat the feedwater in regeneration system.

Table 1 Assumptions in power plant cycles [11, 12]

S.No	Component	Value
1	Power Plant Capacity	660 MWe
2	Pressure drop in steam generator	3 %
3	Efficiency of steam generator	87 %
4	Pressure drop in reheater	1 %
5	Pressure drop of main steam	4 %
6	Pressure drop in steam pipe lines	3 %
7	Throttling loss in turbine	3 %
8	Isentropic efficiency of high pressure turbine	90 %
9	Isentropic efficiency of a low pressure turbine	90 %
10	Mechanical efficiency of a feed pump turbine	98 %
11	Isentropic efficiency of a feed pump	78 %
12	Isentropic efficiency of a main condensate pump/ auxiliary condensate pump	78 % / 75 %
13	Generator efficiency	92 %
14	Atmospheric temperature/pressure	25 ^{0}C/1.01 bar
15	TTD on high side/low side for LPFWHs& HPFWHs	3 K/5 K & 0 K/7 K

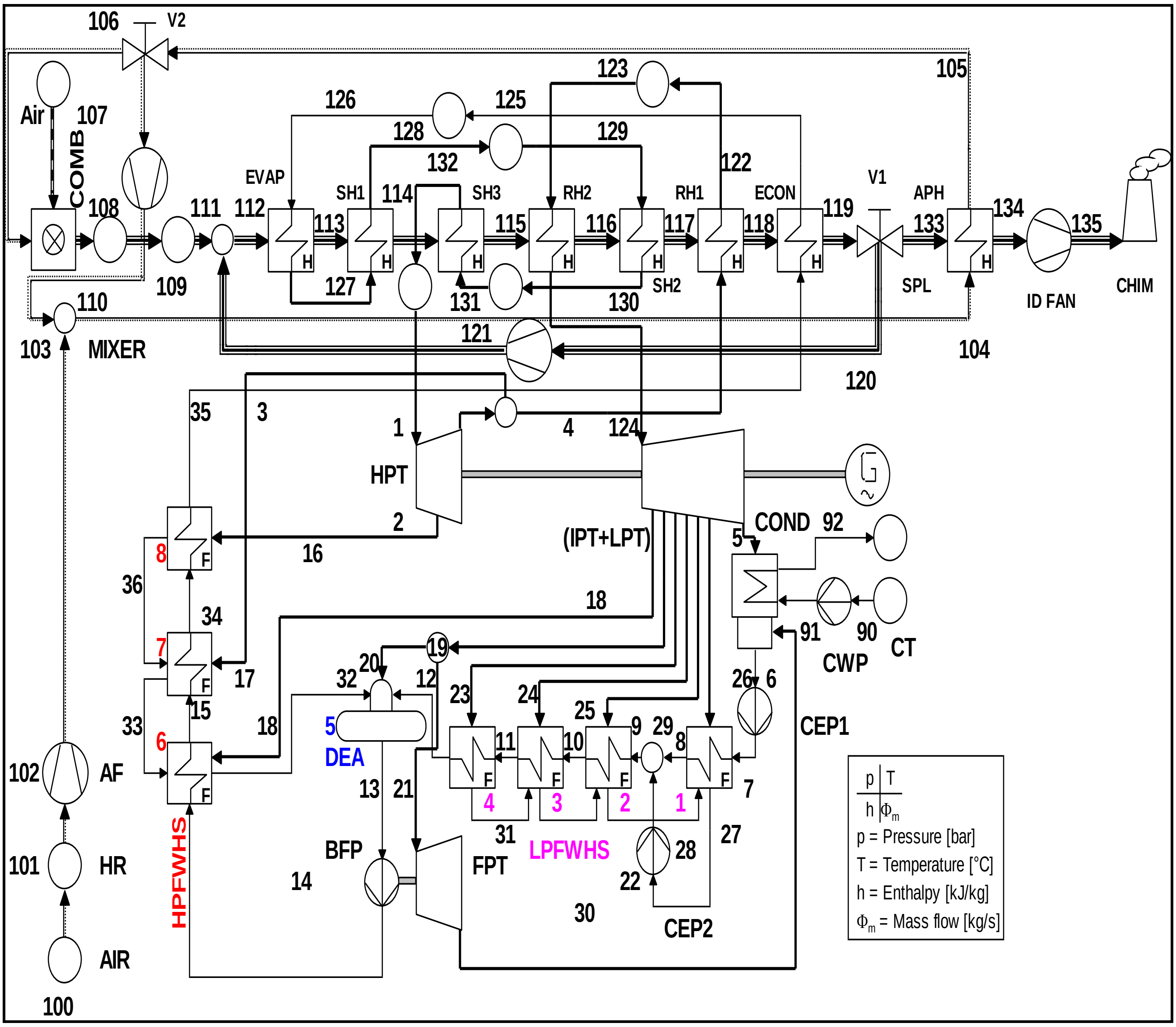

Figure 2: Supercritical Thermal Power Plant capacity of 660 MWe with flue gas heat recovery circuit

3. MATHEMATICAL MODELLING EQUATIONS

The energy balance for the steam generator can be calculated as

$$\dot{Q}_f + \dot{Q}_a = \dot{m}_{ms} x (h_{ms} - h_{fw}) + \dot{m}_{rh} x (h_{rh,o} - h_{rh,i}) + \dot{Q}_{loss} \quad (1)$$

The energy balance of the flows in power plant cycle can be calculated as

$$(\dot{m}_S h_S)_i + (\dot{m}_{FW} h_{FW})_i = (\dot{m}_S h_S)_o + (\dot{m}_{FW} h_{FW})_o \quad (2)$$

The thermal efficiency of the power plant can be calculated as follows

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{m}_{coal} x LHV} \quad (3)$$

Exergy efficiency

$$\varphi_{SG} = \frac{\dot{\psi}_p}{\dot{\psi}_f} \quad (4)$$

$\dot{\psi}_p$: Exergy of products $\dot{\psi}_f$: Exergy of fuel

4. RESULTS AND DISCUSSIONS

Quasi-Newton optimization method is applied that would offer the maximum efficiency of a power plant cycle for certain standard input parameters of industrial power plant. Eight stages of regenerative feed water heater arrangement with and without flue gas for heat recovery heat exchanger devices are considered for the analysis and the simulation and optimum results were compared which are presented in table 2 and shown in figures 3, 4 and 5.

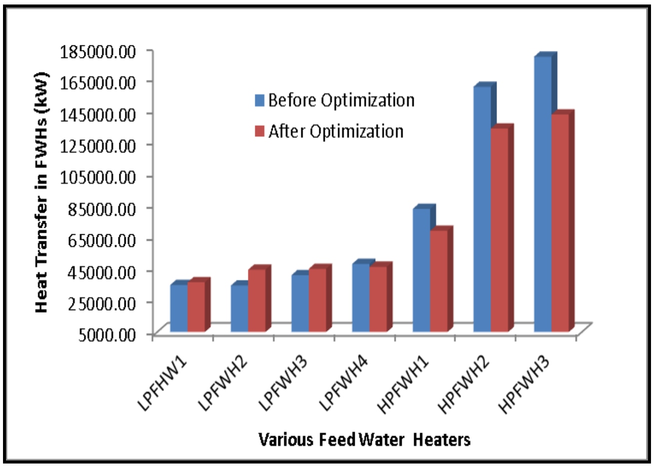

Figure 3: Heat transfer in various feed water heaters before and after optimization

Figure 3 explains the heat transfer in feed water heaters of supercritical power plant cycle before and after optimization. The percentage of heat transfer is less in low pressure feed water heaters (LPFWHs) because water is having the low entropy. Whereas in high pressure feed water heaters (HPFWHs) the percentage of heat transfer is rather high due to superheated steam is extracted from HPT and also the saturated steam has high entropy. It is also observed that the number of iterations required to attain the optimum value for simulation of LPFWHs is high compared to without optimization. For HPFWHs the number of iterations required to obtain the optimum value is less compared to before optimization. The property of entropy of steam and saturated water is greatly affecting the heat transfer aspects of various feed water heaters.

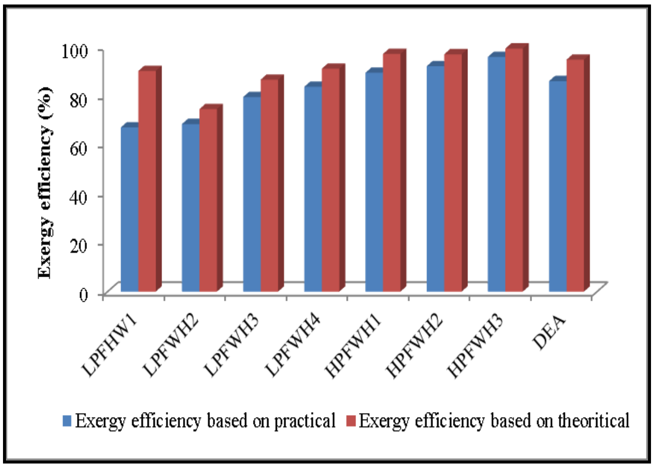

Figure 4: Exergy efficiency based on theoretical and practical values in various feed water heaters after optimization

Exergy efficiency of various feed water heaters both in theoretical and practical aspects of the thermal power plant cycle after optimization is shown in figure 4. It envisages the theoretical exergy efficiency is high compared to practical exergy efficiency. It also indicates the exergy efficiency for closed feed water heaters is high compared to open feed water heater (DEA). In DEA the steam is directly mixing with saturated water coming from the low and high pressure FWHs, whereas the closed feed water heater is an indirect contact process.

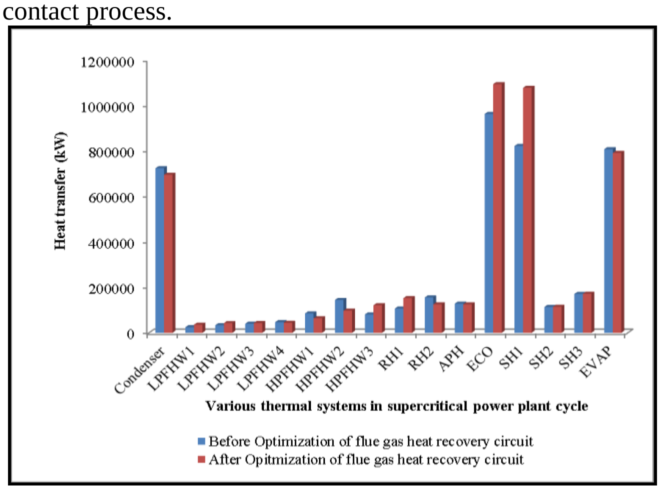

Figure 5: Heat transfer in various thermal systems before and after optimization of flue gas heat recovery circuit.

Figure 5 explains the heat transfer variations in thermal systems before and after optimization of flue gas heat recovery heat exchanger devices. It shows that in Economiser (ECON), Superheater 1(SH1), Evaporator (EVAP) and in Condenser, the heat transfer is more compared to other thermal systems in the power plant cycle. In economiser the heat transfer is directly between the high temperature flue gases and the saturated steam conditions and that is why more heat transfer is occurring. The second largest heat transfer is occurring in evaporator where the enthalpy of steam is high in superheated conditions. The third largest heat transfer is occurring in condenser where the heat is transferring between latent heat content of steam and cold water.

Table 2 Optimum steam extraction pressures of eight feed water heaters in 660 MWe supercritical power plant cycle

Regenerative Feed Water Heaters	**Steam extraction pressures after Optimization**		**660MWe SIPAT stage 1 Plant results**
	Conventional power plant cycle	**Conventional power plant cycle after flue gas heat recovery devices**	
LPFWH1	0.25	0.22	0.26
LPFWH2	0.79	0.70	0.62
LPFWH3	2.04	1.81	2.97
LPFWH4	4.64	4.09	6.25
OFWH5(DEA)	9.80	8.13	11.34
HPFWH1	21.03	16.74	21.70
HPFWH2	48.01	36.29	45.67
HPFWH3	97.14	91.40	64.80
Thermal Efficiency(%) of Plant	40.85	44.31	43.20
Exergy Efficiency(%) of Plant	38.52	41.77	40.95
Number of Optimization iterations	797	1000	--

5. CONCLUSIONS

Today there is an importance of increasing the steam input parameters, in power plant industries to enhance the plant thermal efficiency. In the current research work thermal power plant cycle with a capacity of 660 MWe is simulated in Cycle Tempo 5.0 in order to attain the maximum thermal efficiency as objective function using the Quasi–Newton optimization technique. The obtained results are in good agreement with industrial power sector results. The following conclusions can be drawn as follows.

1. The exergy analysis reveals that the supercritical units after optimization with flue gas heat recovery heat exchanger devices are more efficient compared to the conventional units without optimization.
2. Simulation and exergy analysis are useful in system optimization. They not only indicate the direction of system optimization, but also provide real insights on loss of various components.
3. The number of iterations required to attain the maximum thermal efficiency of supercritical units with heat recovery heat exchanger devices are more compared to conventional supercritical units.
4. The thermal efficiency of supercritical units decreases as the atmospheric temperature increases.

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