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THERMODYNAMICS ANALYSIS AND PERFORMANCE OPTIMIZATION OF A REHEAT – REGENERATIVE STEAM TURBINE POWER PLANT WITH FEED WATER HEATERS

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ABSTRACT

Steam power plants have a huge potential to meet the growing energy demand but its viability has been hampered by its dependence on conventional fossil fuels. One of the ways to minimize fuel consumption and improve effectiveness of thermal power plant is by introducing feed water heaters (FWHs). In this study, thermodynamics performance analysis of a reheat-regenerative steam power plant was carried out using CyclePad version 2 software. The impact of the available feed water heaters on the functionality indices of the selected power was examined. Results of the study show that as the number of feed water heater increases from one to ten, the thermal efficiency and boiler efficiency improve from 42.17% to 45.97% and 79% to 96.4 %, respectively. While the fuel consumption, heat rejected to condenser, heat rate and heat input to the power cycle decreases from 9.697 kg/s to 4.686 kg/s, 209.32 kJ/kg to 129.68 kJ/kg, 8536.87 kJ/kWh to 8318.48 kJ/kWh and 361.11 kJ/kg to 237.98 kJ/kg, respectively. This implies decrease in operation cost of the plant and environmental impacts can be achieved by increasing the number of FWHs. Hence, the importance of FWH revamp performance of steam turbine power plant is established.

Keywords: Thermal efficiency, feed water heater, performance optimization, specific steam consumption, heat input, thermodynamic analysis

NONMENCLATURE

h - Enthalpy (kJ/kg)
T - Temperature (°C)
s - Entropy (kJ/kgK)
$\dot{m}$ - mass flow rate (kg/s)
W_t - Network outpuy (MW)
Q_{in} - Heat input (MW)
v - Specific volume (m^3/kg)
η - Thermal efficiency (%)
Δh_t - Total enthalpy rise of feedwater (kJ/kg)
Δt_{fw} - Total temperature rise of feedwater (°C)

1. INTRODUCTION

The utilization of energy is one of the most important signs showing the developmental stages of countries and living standards of communities. Energy conservation is a key goal of economy and it will continue to be in near future. The most effective way to meet the energy demand is to use energy more efficiently. Based on this fact, analyses of power generation systems are of scientific interest and also essential for the efficient utilization of energy resources [1].

In order to attain optimal effectiveness of steam power plant, numerous ways to utilize available energy more efficiently and extract more power from a current system are being considered by making several modifications [2]. These modifications include: addition of open and closed feed water heaters (FWHs), re-heaters, regenerator etc. [3].

Feed water heating process increases temperature of feed water at inlet to boiler and the increase in feed water temperature leads to drop in the heat requirement in boiler for getting desired state at inlet to steam turbine [4]. Thus, with the reduced heat addition the thermal efficiency gets increased. Improving the power plant efficiency could alleviate the negative effect of fossil fuel consumption on CO_2 emission [5].

In this study, various operating parameters are selected and effects of these parameters on the performance of power plant are determined. Selected operating parameters are: (a) number of feed water heaters (From one to five heaters) and (b) mass flow rates of water addition in deaerator (like 0, 1 and 2% of total mass flow rate of steam generated in boiler). To evaluate performance of the selected power plant, power output, thermal efficiency, specific fuel consumption and heat rate are calculated at different conditions. The performance parameters were to be analyzed using Cyclepad Version2 software.

2. MATERIALS AND METHOD

2.1 Study Area

Egbin steam power plant is a natural circulation steam power plant with total installed capacity of 1320MW comprises of six (6) independent units each having an installed capacity of 220MW [6]. It is modeled as improved Rankine cycle with reheating and regenerative feedwater heating. Natural gas is used as the primary energy source, which is ignited with air under pressure to start the boiler [7].

Figure (1) shows the one unit flow diagram of the selected steam power plant containing 6 units. The design basis of each unit is a nominal 220 MW Reheat-Regenerative cycle. of 45°C, armature temperature rise of 55°C, field temperature rise of 65°C, and with natural circulation with single reheat and duct firing.

2.2 Thermodynamic Analysis

The operation of steam power plant is considered under steady-state condition. The pressure loss throughout the pipelines is assumed negligible. Applying the steady flow energy equation to each of the processes on the basis of unit mass of fluid, and neglecting changes in kinetic and potential energy, the work and heat quantities are evaluated in terms of the properties of the fluid. Energy analysis of each component is given as follow:

Mass balance is given by:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (1)$$

Energy balance is given as:

$$\sum_{in} \dot{E}_{in} + \dot{Q} = \sum_{Out} \dot{E}_{out} + \dot{W} \quad (2)$$

2.2.1 Energy Analysis of Turbine

Work Output of High Pressure Turbine

$$(1 - m_3 - m_4)h_2 - (m_7 h_7 + m_6 h_6 + m_5 h_5) = w_{HPT} \quad (3)$$

Work Output of Intermediate Pressure Turbine

$$m_{12}h_{12} + m_{5a}h_{5a} - (m_{15}h_{15} + m_{14}h_{14} + m_{13}h_{13} + m_{18}h_{18}) = w_{IPT} \quad (4)$$

Work Output of Low Pressure Turbine

$$m_{18}h_{18} - (m_{19}h_{19} + m_{20}h_{20} + m_{21}h_{21} + m_{24}h_{24}) = w_{LPT} \quad (5)$$

Total Turbine Work Output

$W_T = W_{HPT} + W_{IPT} + W_{LPT}$

$$(1 - m_3 - m_4)h_2 + m_{12}h_{12} + m_{5a}h_{5a} + m_{18}h_{18} - (m_7h_7 + m_6h_6 + m_5h_5 + m_{15}h_{15} + m_{14}h_{14} + m_{13}h_{13} + m_{18}h_{18} + m_{19}h_{19} + m_{20}h_{20} + m_{21}h_{21} + m_{24}h_{24}) = W_T \quad (6)$$

2.2.2 Energy Analysis of Heat Input

Heat Input into Reheater

$$m_{12}h_{12} - m_{11}h_{11} = q_{Reheater} \quad (7)$$

Heat Input into Boiler

$$h_1 m_1 - (m_{51}h_{51} + m_{46}h_{46}) = q_{Boiler} \quad (8)$$

Total Heat Addition

$$q_{Total} = q_{Boiler} + q_{Reheater} = m_f LHV_f$$

$$h_1 m_1 + m_{12}h_{12} - (m_{11}h_{11} + m_{51}h_{51} + m_{46}h_{46}) = q_{Total} \quad (9)$$

2.2.3 Energy Analysis of Heat Rejection

Heat Rejection of Condenser

$$q_{Condenser} = m_{27}h_{27} - m_{29}h_{29} - m_{30}h_{30}) \quad (10)$$

2.2.4 Energy Analysis of Pumps

Analysis of Condensate Extraction Pump

$$m_{31}(h_{31} - h_{30}) = w_{CEP} \quad (11)$$

Analysis of Boiler Feed Water Pump

$$m_{44}(h_{45} - h_{44}) = w_{BFP} \quad (12)$$

Total Pump Work

$$w_P = w_{BFP} + w_{CEP}$$

$$m_{44}(h_{45} - h_{44}) + m_{31}(h_{31} - h_{30}) = w_P \quad (13)$$

2.2.5 Network Output of Plant

Net Work Output = Total Turbine Work Output – Total Pump Work Input

$$w_{NET} = w_T - w_P$$

$$(1 - m_3 - m_4)h_2 + m_{12}h_{12} + m_{5a}h_{5a} + m_{18}h_{18} - (m_7h_7 + m_6h_6 + m_5h_5 + m_{15}h_{15} + m_{14}h_{14} + m_{13}h_{13} + m_{18}h_{18} + m_{19}h_{19} + m_{20}h_{20} + m_{21}h_{21} + m_{24}h_{24}) - m_{44}(h_{45} - h_{44}) - m_{31}(h_{31} - h_{30}) = w_{NET} \quad (14)$$

2.2.6 Analysis of Feed Water Heaters:

Energy Balance

LPH 1: $m_{23}h_{23} + m_{40}h_{40} + m_{36}h_{36} = m_{37}h_{37} + m_{38}h_{38}$ (15)

LPH 2: $m_{21}h_{21} + m_{43}h_{43} + m_{37}h_{37} = m_{41}h_{41} + m_{40}h_{40}$ (16)

LPH 3 $m_{19}h_{19} + m_{41}h_{41} = m_{42}h_{42} + m_{43}h_{43}$ (17)

HPH 5: $m_{15}h_{15} + m_{48}h_{48} + m_{50}h_{50} = m_{47}h_{47} + m_{49}h_{49}$ (18)

HPH6: $m_{10}h_{10} + m_{49}h_{49} = m_{50}h_{50} + m_{51}h_{51}$ (19)

Deaerator:

$$m_{16}h_{16} + m_{42}h_{42} + m_{47}h_{47} = m_{44}h_{44} \quad (20)$$

2.2.7 Cycle Efficiency and Performance Parameters

BoilerEfficiency=

$$\frac{\{(\textbf{steam value}\frac{kg}{hr}).(h_2 - h_1).100\}}{(\textbf{fuel consumption}\frac{kg}{hr}).(\textbf{fuel low calorific value}\frac{Kcal}{kg})} \quad (21)$$

Thermal Efficiency:

η = $[(1 - m_3 - m_4)h_2 + m_{12}h_{12} + m_{5a}h_{5a} + m_{18}h_{18} - (m_7h_7 + m_6h_6 + m_5h_5 + m_{15}h_{15} + m_{14}h_{14} + m_{13}h_{13} + m_{18}h_{18} + m_{19}h_{19} + m_{20}h_{20} + m_{21}h_{21} + m_{24}h_{24}) - m_{44}(h_{45} - h_{44}) - m_{31}(h_{31} - h_{30})] \; / \; [m_1h_1 + m_{12}h_{12} - (m_{11}h_{11} + m_{51}h_{51} + m_{46}h_{46})]$ **(22)**

Specific Steam Consumption

SSC = $\frac{3600}{Network}$ (23)

Specific Fuel Consumption in Boiler

$$SFC = \frac{\{SP.(h_s - h_w)\}}{(BE.LHV)} \quad (24)$$

where SFC is specific fuel consumption; SP is steam produced per second; h_s is enthalpy of steam at turbine inlet; h_w is enthalpy of condensate; BE is boiler efficiency; and LHV is Lower heating value of fuel (47.141MJ/kg).

Heat Rate

Heat rate in steam power plant is given by:

Heat rate = $\frac{3600}{\eta} kJ/_{kWh}$ (25)

Total Enthalpy Rise of Feedwater in Regenerative Cycle

The total enthalpy rise of feed water for *n* heaters by regenerative feedwater heating is given by Nag [8]:

$$\Delta h_t = \frac{n}{n+1}(h_S - h_c) \quad (26)$$

where, Δh_t is the total enthalpy rise of feed water for *n* heaters by regenerative feedwater heating, n is the number of feedwater heaters, h_s is the saturated steam enthalpy and h_c is the condensate (saturated liquid leaving condenser) enthalpy.

Total Temperature Rise of Feedwater

The total temperature rise of feedwater, Δt_{fw} due to regeneration for the maximum cycle efficiency is given by [8]:

$$\Delta t_{fw} = \frac{n}{n+1}\Delta t_{BSC} \quad (27)$$

where,

Δt_{BSC} = Boiler saturation temperature - Condenser temperature

2.3 Performance Assessment of Thermal Power Plant Using Cycle Pad

In this study, performance assessment of a reheat – regenerative steam power plant was carried out using cycle pad. Rankine cycle was modified using CyclePad and the effects of regeneration on the cycle's thermal efficiency, specific fuel consumption, boiler efficiency, specific steam consumption and condenser loss were computed. Figures 2 shows reheat-regenerative cycle on cyclepad.

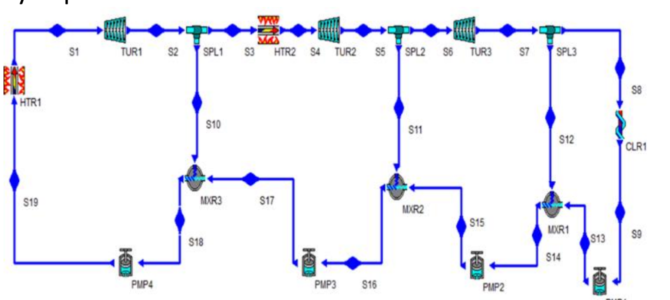

Figure 2: Reheat Regenerative Cycle on CyclePad

3.0 Results and Discussion

The thermodynamic properties of steam including pressure, temperature, enthalpy, entropy, specific volume and mass flow rates at state points (Figure 2) were calculated using cyclepad software and presented in Tables 1 to 3. Tables 1 to 3 show the state thermodynamic properties for steam power plant without feed water heater, with one and two FWHs, respectively. Table 4 compares the computed performance parameters (using CyclePad) for the power cycle without feedwater heater and with one to ten feedwater heaters. To assess the optimal performance of feed water heater, the number of feed water heaters was increased from 5 to 10 and the performance parameters are presented in Table 4.

Table 1: State thermodynamic properties for Rankine cycle without FWH.

Location	T(̊ C)	P(kPa)	h(kJ/kg)	s(kJ/kgK)	v(m^3/kg)	ṁ(kg/s)
S1	545	12990	3457	6.59	0.0267	110.6
S2	538	12500	3444	6.59	0.0275	110.6
S3	541	12500	3452	6.60	0.0276	110.6
S4	538	12295	3446	6.60	0.0280	110.6
S5	42.67	8.500	2071	6.60	13.490	110.6
S6	42.67	8.500	2071	6.60	13.490	110.6
S7	43.08	12990	191.8	0.6078	0.0010	110.6

Tables 2 State thermodynamic properties for reheat-regenerative cycle with one FWH

Location	T(̊ C)	P(kPa)	h(kJ/kg)	s(kJ/kgK)	v(m^3/kg)	ṁ(kg/s)
S1	545	12990	3457	6.59	0.0267	110.6
S2	538	12500	3444	6.59	0.0275	110.6
S3	541	12500	3452	6.60	0.0276	110.6
S4	538	12295	3446	6.60	0.0280	110.6
S5	538	12295	3446	6.60	0.0280	108.8
S6	42.67	8.500	2071	6.60	13.49	108.8
S7	42.67	8.500	178.7	0.6078	0.0010	108.8
S8	43.06	12295	191.1	0.6078	0.0010	108.8
S9	538.0	12295	3446	6.60	0.0280	1.76
S10	55.53	12295	242.9	0.7685	0.0010	110.6
S11	55.56	12990	243.6	0.7685	0.0010	110.6

Table 3: State thermodynamic properties for reheat-regenerative cycle with two FWHs.

Location	T(̊ C)	P(kPa)	h(kJ/kg)	s(kJ/kgK)	v(m^3/kg)	ṁ(kg/s)
S1	545.0	12990	3457	6.59	0.0267	110.6
S2	538.0	12500	3444	6.59	0.0275	110.6
S3	538.0	12500	3444	6.59	0.0275	100.6
S4	541.0	12500	3452	6.60	0.0276	100.6
S5	538.0	12295	3444	6.60	0.0280	100.6
S6	538.0	12295	3446	6.60	0.0280	98.83

S7	42.67	8.500	2017	6.60	13.490	98.83
S8	42.67	8.500	178.7	0.6078	0.0010	98.83
S9	43.06	12295	191.1	0.6078	0.0010	98.83
S10	538.0	12500	3444	6.59	0.0275	10.01
S11	538.0	12295	3446	6.60	0.0280	1.760
S12	56.77	12295	248.0	0.7848	0,0010	100.6
S13	56.78	12500	248.2	0.7841	0.0010	100.6
S14	125.9	12500	537.4	1.5800	0.0011	110.6
S15	126.0	12990	538.0	1.5800	0.0011	110.6

Considering the above performance parameters, it was observed that the highest thermal efficiency (45.37%) of the actual steam power cycle was obtained when working with five heaters. That is the actual number of heaters in the existing selected steam power plant. The steam power cycle was simulated by increasing the number of heaters to ten and the cycle efficiency increased to 45.97%. But the efficiency gain (Δη) successively diminishes with increase in the number of heaters (Figure 4). According to Nag [8], improvement in cycle thermal efficiency varies directly to the increase in feed water temperature, the thermal efficiency increment follows the law of diminishing return with addition in the number of heaters. From this study, the highest increment in thermal efficiency (2.13%) is brought about by the first heater. The increments for each additional heater thereafter successively diminish in efficiency. From Figure 3, it is observed that significant gain in cycle efficiency occurred between first and sixth heater. Hence, increasing the feed water heaters above six might not give significant gain in cycle of efficiency of the selected plant. In practice, up to five to seven points of extraction are often used.

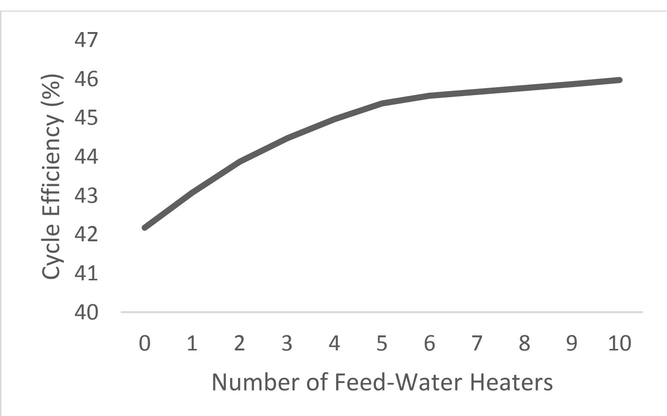

Figure 3: Plot of Cycle Efficiency against Number of FWHs

With increase in the number of feed water heaters, there is increase in cycle thermal efficiency. As the cycle thermal efficiency increases, heat rate decreases from 8536.87 kJ/kWh to 8318.48 kJ/kWh.

In Table 4**,** it is shown that the network output decreases from 150.22 MW to 102.89 MW. On the contrary, specific steam consumption increases from 0.0234 kg/kWh to 0.0370 kg/kWh. When the plant operates with 1, 2, 3, 4 and 5 heaters increase in SSC is approximately 2.5%, 8.8%, 11.8%, 13.6% and 15.07%, respectively. Comparing this results with 6 to 10 heaters, SSC increased from 16.12% to 16.98%. This shows that in regenerative cycle SSC increases for power generation, because it decreases the useful network output and increase the steam flow.

Considering the specific fuel consumption, SFC decreases significantly with increase in the number of feedwater heaters. When the plant operates with five heaters, SFC varies from 8.975 kg/s to 5.530 kg/s. The SFC further decreased when the plant was simulated using 6 to 10 feed water heaters and the value ranges from 5.215 kg/s to 4.686 kg/s. This variation is more important than the previous parameter (SSC) due to the fact that water is less expensive than the fuel burnt. As regard heat rejected in condenser and heat input to the cycle, these two parameters decrease with increase in the number of feedwater heaters. Heat rejected in condenser and heat input in the cycle decreases from 205.99 kJ/kg to 129.68 kJ/kg and 355.38 kJ/kg to 237.98 kJ/kg for the 10 feedwater heaters.

3.1 Total Enthalpy Rise and Total Temperature Rise of Feedwater in Regeneration Cycle

Equations (23) and (24) are the equations for total enthalpy rise and total temperature rise of feedwater heater in regenerative cycle. Table 5 shows the total enthalpy rise and total temperature rise for Rankine cycle with no feedwater heater and regenerative cycle with 1 to 10 feedwater heaters. From Table 5, both enthalpy rise and temperature rise increase with increase in the number of feedwater heaters. As the number of heaters increase, more is the total temperature rise of feedwater (Δt_{fw}), by regeneration, less becomes the heat addition to water in the boiler, more becomes the mean temperature of heat addition, and more is the cycle efficiency.

Table 5: Total Enthalpy Rise and Total Temperature Rise of Feedwater in Regeneration Cycle

No. of Heaters	Temperature Rise (Δt_{fw}) (°C)	Enthalpy Rise (Δh_t) (kJ/kg)
0	0.00	0.00
1	247.67	1639.15

2	330.22	2185.53
3	371.50	2458.73
4	396.26	2622.64
5	412.78	2731.92
6	424.57	2809.97
7	433.41	2868.51
8	440.29	2914.04
9	445.80	2950.47
10	450.30	2980.27

4.0 Conclusions

The influence of the number of FWHs on the performance parameters of the selected steam turbine power plant was examined in this study. The effects of regenerative feedwater heating on power plant performance may be summarized as follows:

(i) It significantly increases the cycle efficiency and reduces the heat rate (reducing operating cost).

(ii) It increases the specific steam consumption. This invariably leads to decrease in network output.

(iii) It decreases the fuel consumption, heat rejected in condenser and heat input to the cycle. This invariably can lead to reduction in operation cost and environmental impact.

(iv) Raising the numbers of FWHs increases the thermal efficiency of the plant. Hence as network reduces, heat added reduces.

(v) It significantly increases the total temperature rise and total enthalpy rise of feedwater.

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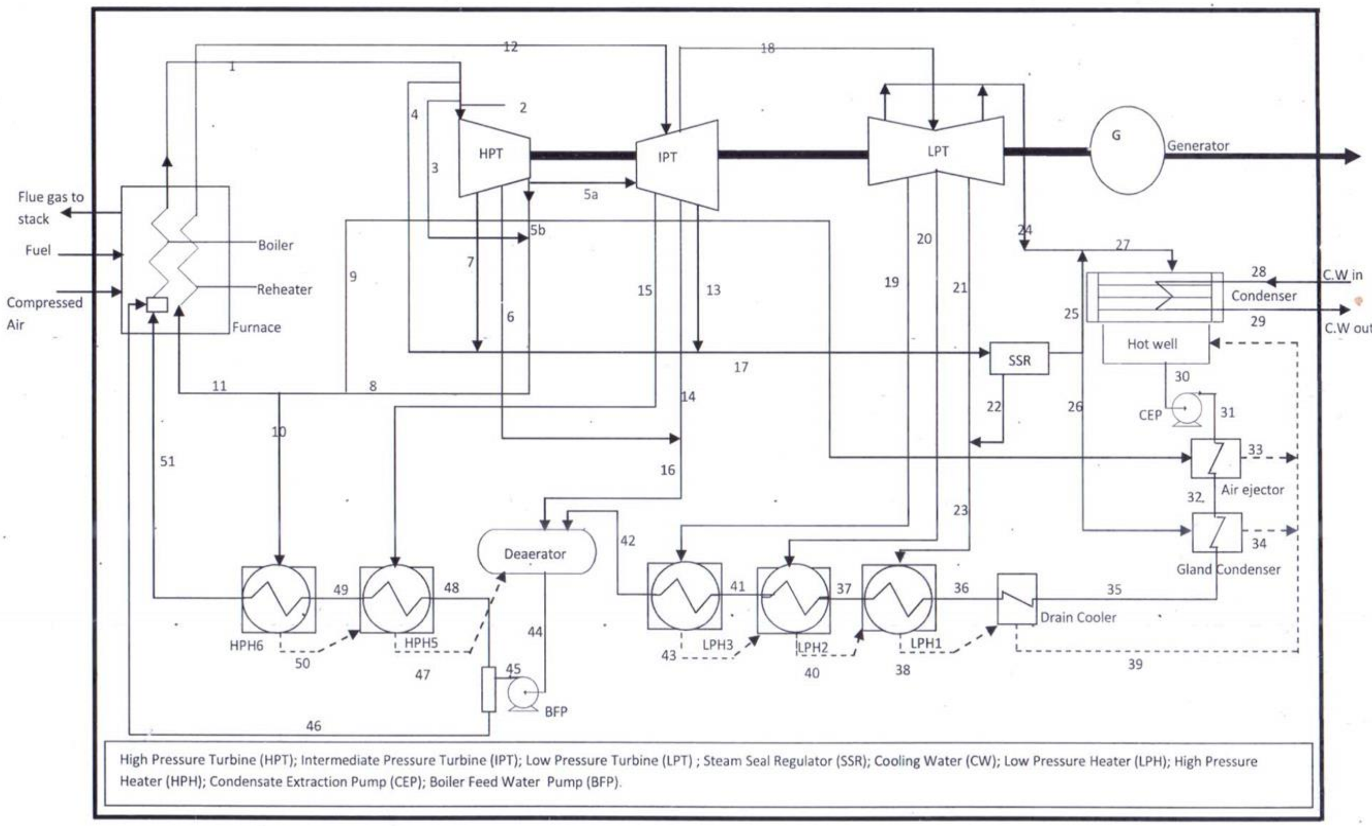

Figure 1: Egbin Power Plant Process Flow Diagram

Table 8: Comparison of performance parameters with various number of FWHs

No. of feed-water heaters	Thermal Efficiency (%)	Network Output (MW)	Heat rate (kJ/kwh)	Back work ratio (%)	Specific steam consumption (kg/kWh)	Boiler Efficiency (%)	Fuel consumption (kg/s)	Heat rejected in Condenser (kJ/kg)	Heat input to the cycle (kJ/kg)
0	42.17	150.22	8536.87	93.9	0.0234	79.0	9.697	209.32	361.11
1	43.07	150.24	8534.85	94.0	0.0240	84.0	8.975	205.99	355.38
2	43.87	136.59	8530.81	95.0	0.0263	87.0	7.872	187.04	322.82
3	44.47	120.91	8522.73	95.0	0.0298	91.0	6.657	165.23	285.47
4	44.97	104.28	8492.57	97.0	0.0345	94.0	5.548	142.30	245.90
5	45.37	104.15	8491.07	97.4	0.0397	94.6	5.530	140.50	244.60
6	45.57	103.98	8489.17	97.7	0.0461	95.2	5.215	139.80	242.65
7	45.67	103.86	8398.07	97.9	0.0536	95.6	4.851	138.70	241.35
8	45.77	103.45	8390.67	98.0	0.0625	95.8	4.716	137.89	240.95
9	45.87	103.25	8368.17	98.2	0.0730	96.0	4.706	130.96	239.87
10	45.97	102.89	8318.48	98.6	0.0854	96.4	4.686	129.68	237.98