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COMPARATIVE ENERGY AND EXERGY ANALYSIS OF A POWER PLANT WITH SUPER-CRITICAL AND SUB-CRITICAL

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ABSTRACT

The aim of this study that how to effect live steam parameters reheat and feed water preheater numbers on efficiencies of energy and exergy at coal-fired power plants. Moreover, two desuperheaters and a regenerative turbine are added USCPP (Case 3) to approach best results. Soma Power Plant (Case 1) consists of one reheat stage, two HPRHs and four LPRHs with one DEA. It is operated sub-critic and coal is used for a fuel. Live steam conditions of Soma Power Plant set at 13,92 MPa and 540 °C, and the reheat steam is reheated to 540 °C. Supercritical Power Plant (Case 2) consists of the same main components of Case 1. However, steam parameters of Case 2 are increased to 262.5 Bar and 600 °C to determine impact of the steam parameters on power plant efficiencies. USCPP which consists of two reheat stages, four HPRHs, six LPRHs with one DEA is designed to generate live steam under nominal conditions of 30 Bar and 600 °C. Besides, reheat steam are heated to 620 °C. Simulations have been carried out Ebsilon Professional software and pressure drops at preheaters and reheats are also considered. Some assumptions are made in the analysis. The thermal and exergy efficiencies of USCPP increase by 9.241 and 8.06 percentage points compared with Soma power plant, respectively. The results of this study that live steam parameters which are increased from sub-critical values to super-critical values have enormous influence on energy and exergy efficiencies. Secondly, adding second reheat stage has positive impact to improve power plant efficiencies. Finally, augmenting feed water preheater number, adding two desuperheater and one regenerative turbine increase power plant efficiencies. However, optimum numbers of feed water preheaters are determined considering economic parameters.

Keywords: *Thermal Efficiency, Exergy Efficiency, Sub-Critical Power Plant, Ultra-Supercritical Power Plant*

INTRODUCTION

Energy is needed for almost every stage of modern life and achieving proper energy gained more attention for both producers and consumers. In addition, the energy consumption level is used as the criteria to indicate the development level of the countries. The level of energy dependency and the quantity of energy consumption in many developed countries are higher than developing countries [1]. On the other hand, global warming has been one issue of great concern in the world. There is very good correlation between the greenhouse gas concentration in atmosphere and the global temperature. CO_2 accounts for over 50% of the contributions of greenhouse gases causing global warming. In the world, 30-40 % of total CO_2 emissions come from coal-fired power plants [2]. Economic power generation with lowest possible fuel consumption is the main challenge for all the engineers working in power generation industry [3].

Energy is also very essential for economic and social development and improved quality of life in Turkey, as in other countries [4]. However, in Turkey, 50% of the amount of electricity generated from thermal power plants is depended on imported fuel sources, especially natural gas [5]. As a result, energy conservation is extremely significant for energy security, environmental protection, emission and imported fuel reduction in Turkey. Even though Turkey has many power plants in which coal is used as a fuel, they have low thermal and exergy efficiency. For this reason, they have to be renewed to increase their thermal and exergy efficiency. Power plants should be operated at a high parameter condition in supercritical and ultra-supercritical domains to accomplish this goal. Power plant parameters have been enhanced extremely over the past decades. Live steam pressure can reach 30 MPa and live steam temperature has increased to 600 °C [6]. Therefore, USCPPs can be one of the best choices to decrease external dependence.

Analyses of power generation systems are of scientific interest and also essential for the efficient utilization of energy resources. The most commonly used method for analysis of an energy-conversion process is

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the first law of thermodynamics. Furthermore, exergetic analyses provide a tool for a clear distinction between energy losses to the environment and internal irreversibility in the process [7].

In the literature, there exists a number of paper concerning energetic and exergetic performances of coal-fired thermal power plants. For instance, Aljundi determines the largest energy and exergy losses for Al-Hussein Power Plant in Jordan by analyzing the system components separately [8]. Huseyin et al. analyzed comparatively the performance of nine thermal power plants under control governmental bodies in Turkey, from energetic and exergetic viewpoint [5]. Doseva and Chakyrova have analyzed energy and exergy analysis of cogeneration system with biogas engines [9]. Wolley et al. have researched effect of waste heat energy at energy efficiency [10]. Karakurt and Gunes show the effect of part load condition at power plant [11]. Akkaya have investigated influence of ambient condition at organic rankine cycle [12]. Ozdil et al. have worked on cogeneration system in food industry [13]. Xu and Zhou investigated thermodynamic and techno-economic analyses at coal-fired power plants by adding outer steam cooer and the regenerative turbine [6]. Oktay analyzed the irreversibilities, exergy efficiency and improvement factor of plant components for a fluidized bed thermal power plant in Turkey [14]. Kaushik has investigated irreversibilities of Brayton cycle based on ecological optimization criterion and analyzed thermo-economic optimization and parametric study of an irreversible regenerative Brayton cycle. Moreover, Kaushik has analyzed efficient power optimization of Brayton heat engine with variable specific heat of the working fluid and investigated energy and exergy analysis of annular thermoelectric heat pump and thermoelectric heat pump [15,16,17,18,19]. Rashidi and Aghagoli investigated the first and second law analysis for the cycle and optimization of the thermal and exergy efficiencies by changing turbine inlet pressure, boiler exit steam temperature, and condenser pressure [7]. Li et al. presented thermodynamic analysis and design optimization of a double reheat system in an ultra-supercritical power plant [20]. Reddy et al. investigated appropriate reheat parameters for double reheat units [21]. Adibhatla and Kaushik performed an energetic and exergetic analysis on a 660 MWe coal fired supercritical thermal power plant at 100%, 80% and 60% of normal continuous rating conditions under constant pressure as well as pure sliding pressure operation [3].

In this paper, three thermal power plants have been analyzed. The objectives of the current study are as follows, (1) to present a single reheat sub-critic power plant with six-stage extractions regenerative heaters (Soma Power Plant); (2) to present a single reheat super-critical power plant with six-stage extractions regenerative heaters; (3) to present a double reheat ultra-super-critical power plants with ten-stage extractions regenerative heaters; (4) to measure energy and exergy efficiency of these power plants. All these three systems, power generation efficiencies, total energy input amounts and exergy efficiency are compared and discussed. This paper aims to show that how to improve power generation efficiency and exergy efficiency at power plants in Turkey with the various steam parameters.

BRIEF INTRODUCTION OF THE THERMAL PERFORMANCE EVALUATION CRITERIA

Power generation efficiency and heat rate are commonly used in the electric power industry to evaluate thermal performance of power generation units [22]. Based on a coal-fired power plants, the power generation efficiency η_I is the ratio of P_{gen} to E_{total}. Heat rate is defined as follows:

$$q = (E_{total} \times 3600) / \mathrm{P}_{gen} = 3600 / (\mathrm{P}_{gen} / E_{total}) = 3600 / \eta_I \tag{1}$$

where E_{total} refers to the total energy input per unit time. Theoretically, E_{total} is the total energy entering the system, and includes the chemical energy of coal, the energy of air and the energy of makeup water. To simplify the calculation, the quantitative value of E_{total} is considered as the chemical energy of coal, which equivalent to the low heat value (LHV) of coal input per unit time.

P_{gen} refers to the power generated by the steam turbine. E_{total} and P_{gen} have the same unit of measurement (kW, MW, or GW). The number 3600 refers to 3600 kJ/kWh. The unit of heat rate is kJ/kWh.

Chemical exergy of fuels calculates constitutive components of fuels. Therefore, Szargut ve Stryrlska develop 'φ' value which refers to fuel exergy rate of fuel lower heating value [23]:

$$\varphi = B_0 / Hu \tag{2}$$

where B_0 refers to fuel exergy value and Hu refers to fuel lower heating value. The calculation of φ is defined as follow:

$$\varphi = 1,0437 + 0,1882(h/c) + 0,0610(o/c) + 0,0404(n/c) \tag{3}$$

For the exergy of solid fuels $B_{0,solid}$ is defined as follows:

$$B_{0,solid} = \varphi(Hu + w.h_{fg})) \tag{4}$$

$$B_g = B_{0,solid} \times \dot{m}_{coal} \tag{5}$$

The exergy efficiency of the power plants (η_{II}) :

$$\eta_{II} = W_{out} / B_g \tag{6}$$

where B_g refers to total exergy input of solid fuel. Analysis of coal used for this study is shown at Table 1. Besides, LHV of coal is 8350 kJ/kg [24].

Table 1. Analysis of coal used for the study

Parameter	Symbol	Percentage of constituent
Carbon	c	42.75
Hydrogen	h	1.60
Nitrogen	n	0.50
Oxygen	o	22.45
Ash	-	45.00
Moisture	w	20.00

CASE 1 : TYPICAL SUB-CRITIC POWER PLANT WITH SINGLE REHEAT STAGE IN TURKEY (SOMA)

Configuration of Case 1

Typical coal-fired power plant with single reheat in Turkey is selected at the Case 1. The simplified process flow diagram of the sub-critic power plant is shown Figure 1. The power output of the single reheat system under turbine heat acceptance load condition is 165 MW. The plant consists of turbine stages, two HPRHs, four LPRHs with one DEA, GEN, CON and two FWPs. The live steam conditions are the same of Soma Power Plants. Live steam temperature and pressure are chosen 540 °C and 139 bar, respectively. The reheated steam is heated at 540 °C and the exhaust steam pressure of the steam turbine is set to 7.5 kPa. The live steam flows HP turbine and the exhaust steam of the HP turbine goes to HPRH1 and boiler to reheat 540 °C. The reheated steam at the boiler flows IP 1 turbine section. The steam is extracted for HPRH1 before going to DEA stage. The steam flows through the LP turbine and goes into the CON. The steam is extracted four times at specific pressures for LPRHs.

System simulation and main assumptions

In this study, simulations have been carried out Ebsilon Professional software which includes the thermodynamic cycle and energy equilibrium of the thermal systems in the power plant [25]. The following assumptions are made in analysis.

(1) The operation of the power plant is considered to be in a steady state;

(2) The mean isentropic efficiencies of turbine stages and efficiency of boiler for Case 1 are equal 0.85 and 0.85, respectively;

(3) In the different stages of the HP, IP and LP turbines, the mean isentropic efficiencies and efficiency of boiler for Case 2-3 are equal to 0.88, 0.91, 0.87 and 0.90, respectively [22];
(4) Efficiency of the generator and pumps for are chosen 0.98 and 0.80, respectively;
(5) Pressure drop in regenerative heaters: 2% inlet pressure at steam side, negligible at water side [26];
(6) Pressure drop in reheat stages: 10% cold side pressure of first and second- stage reheat steam [27].

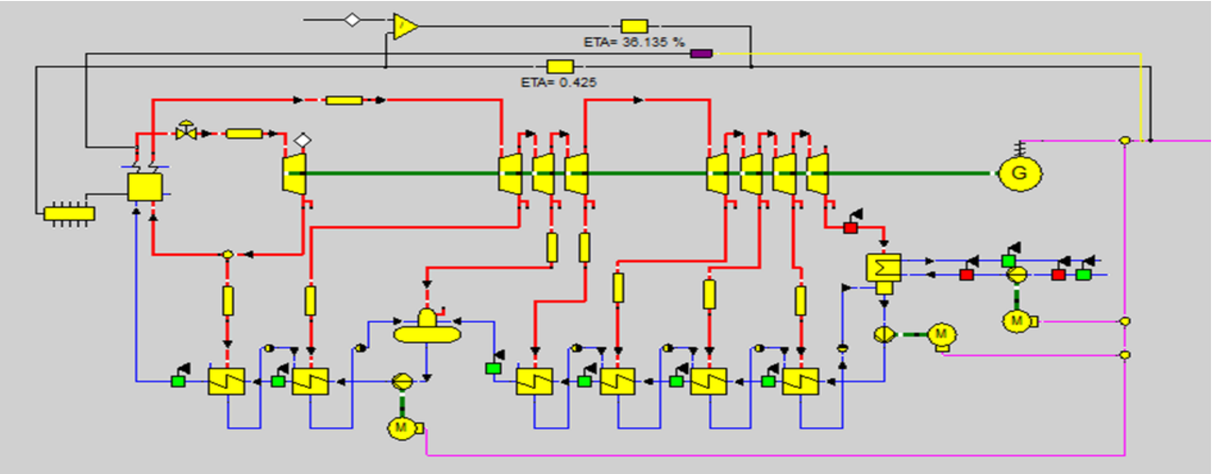

Figure 1. Process diagram of Case 1

CASE 2 : SINGLE REHEAT SYSTEM WITH SIX-STAGE EXTRACTION STEAM

Configuration of Case 2

In this case, efficiencies of the power plant are enhanced by increasing live steam parameters from sub-critical values to super-critical values. Figure 2 shows process flow diagram of Case 2. The live steam parameters are set to 262.5 bar and 600 °C, reheat steams are heated to 610 °C. The exhaust steam of HP turbine flows the boiler to reheat and then enters IP 1 turbine. The location of the extraction points are placed according to the basic principle of power plant design. More specifically, the extraction point of HPRH1 is located at the HP turbine exhaust port. The extraction point of HPRH2 is located between HPRH1 and deaerator where is located at IP 1 turbine exhaust port. The extraction points of LPRH3 and LPRH4 are arranged IP 2 turbine. The extraction point of LPRH5 and LPRH6 are located at LP turbine.

The feed-water enthalpy rise of regenerative system is equivalent to each other [22]. The reheat pressure of Case 1 and Case 2 are chosen 31.38 bar and 78.6 bar, respectively. The first and second-stage reheat pressure of Case 3 are chosen 90 bar and 27 bar. Because, the first and second stage reheat pressure are equal to 30% of the live steam pressure and first reheat pressure, respectively [28].

Process simulation and performance evaluation of Case 2

Table 2. Energy and exergy performances comparison of Case 1 and Case 2

Performance index	Case 1	Case 2
Total energy input (MW)	456.62	2279.14
Power output (MW)	165.00	1000.00
Heat rate (kJ/kWh)	9962.72	8204.90
Decrement in heat rate (kJ/kWh)	-	1757.82
Power generation efficiency (%)	36.135	43.876
Efficiency increment (%)	-	7.741
Consumption of coal (kg/s)	54.68*	272.95
Total exergy input (MW)	523.29	2611.90
Exergy efficiency (%)	31.53	38.28
Exergy efficiency increment (%)	-	6.75

*for 1000 MW power plant, fuel consumption of Case 1 will be 331.39 kg/s.

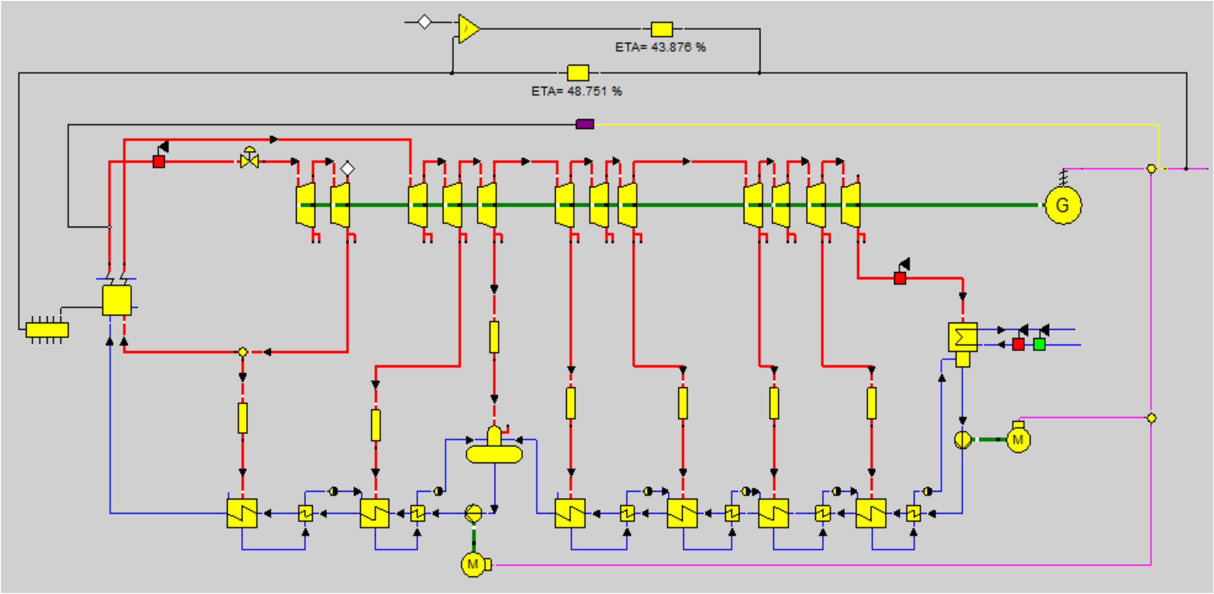

Figure 2. Process diagram of Case 2

The Ebsilon Professional software is used to simulate all the systems in this paper. The thermal and exergy performances Case 1 and Case 2 are compared with Table 2. It is obvious to see that the heat rate of Case 2 decreases 1757.82 kJ/kWh. The power energy efficiency of Case 2 increases by 7.741 % point compared with that of Case 1. Moreover, exergy efficiency of Case 2 rises 6.75% point and consumption of fuel reduces 58.44 kg/s. Rise of the power generation efficiency and reduction of fuel consumption show that release of the CO_2 emission decreases.

5. CASE 3 : DOUBLE REHEAT SYSTEM WITH REGENERATIVE TURBINE AND TWO DESUPERHEATERS

Reheat technology is one of the outstanding examples, which improves efficiency by increasing mean temperature of the endothermic process. Below the line of T-s diagram represents work out. Because of that, this square is increased by adding second reheat stage compared with the other cases. Efficiency of the Carnot cycle is the reference for all the power plant to optimize. Feed water temperature should be increased before entering the boiler to approach of Carnot cycle efficiency. For this reason, four new regenerative heaters are added to increase final feedwater temperature. Moreover, after first and second reheat stage at the turbines, extraction steams reach high temperature to flow for RHs. Because of that desuperheaters can be used to evaluate this high temperature to increase final feed water temperature. Furthermore, second FWP consumes high electricity to increase boiler feed water pressure after deaerator. It increases feed water pressure from 29 bar to 310 bar. Therefore, regenerative turbine is added the system to generate electricity for second feed water pump. For details, Case 3 consists of double reheat stage, four HPRHs, six LPRHs with one DEA, two desuperheaters and one regenerative turbine. Second reheat steam is heated to 620 °C. Figure 3 illustrates process diagram of Case 3.

6.2 Process simulation and performance evaluation of Case 3

The thermal performance of Case 3 and Case 2 are shown at Table 3. Energy input of Case 3 drops 75.36 MW and power generation efficiency of Case 3 rises 1.50 % points compared with Case 2. The reason is that final feed water temperature increases to be added desuperheaters and RHs, and also energy consumption of the auxiliary equipment decreases because of adding regenerative turbine. The rise of final feed water temperature is 38.52 °C and this is significant indicator to decrease fuel consumption. Moreover, exergy efficiency of Case 3 increases 1.31% compared with Case 2. This shows that increasing exergy efficiency affects potential work out of power plant.

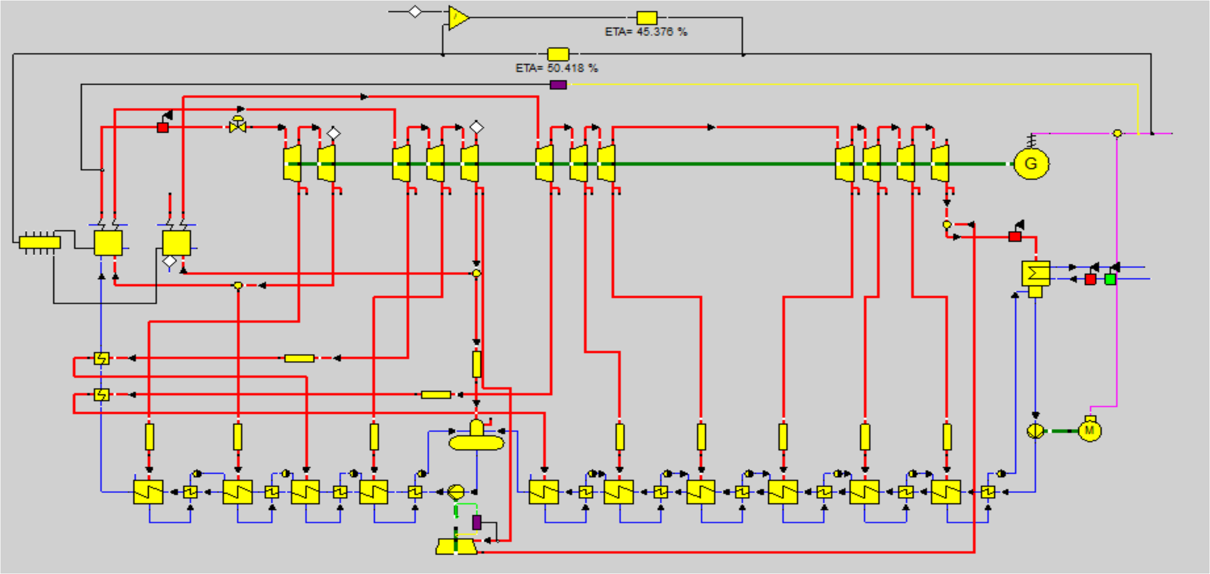

Figure 3. Process diagram of Case 3

Table 3. Energy and exergy performances comparison of Case 2 and Case 3

Performance index	Case 2	Case 3
Total energy input (MW)	2279.14	2203.78
Power Output (MW)	1000.00	1000.00
Heat rate (kJ/kWh)	8204.90	7933.60
Decrement in heat rate (kJ/kWh)	-	271.29
Power generation efficiency (%)	43.876	45.376
Efficiency increment (%)	-	1.500
Consumption of coal (kg/s)	272.95	263.92
Total exergy input (MW)	2611.90	2525.55
Exergy efficiency (%)	38.28	39.59
Exergy efficiency increment (%)	-	1.31
Final feed water temperature (°C)	299.05	337.57

DISCUSSION

The thermal performance of all cases is shown in Figure 4. The thermal and exergy efficiencies of Case 1 are 36.135% and 31.53%, respectively. Case 1 which is sub-critic consists of single reheat stage, two HPRHs, four LPRHs with one DEA.

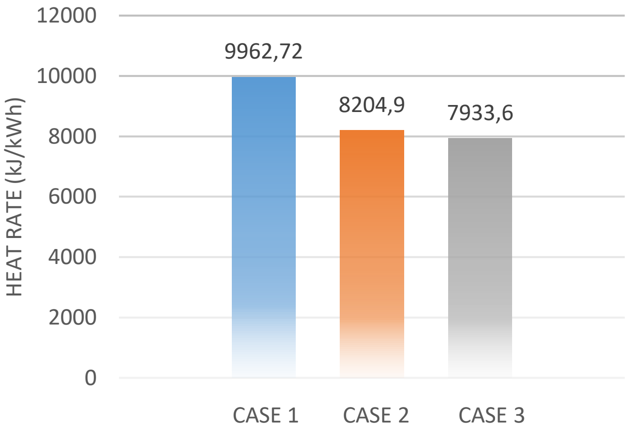

Figure 4. Comparison of the heat rate

The thermal and exergy efficiencies of Case 2 are 43.876% and 38.28%, respectively. The thermal and exergy efficiencies of Case 3 are also 45.376% and 39.59%, respectively. This analysis shows that increasing live steam parameters has significant role for thermal and exergy efficiencies. Furthermore, Case 3 which is operated ultra-supercritical steam parameters comprises of double reheat stage, four HPRHs, six LPRHs with one DEA, two desuperheaters and one regenerative turbine. Final feed water temperature of Case 3 rises 38 °C compared with Case 2 because of adding two desuperheaters and RHs. After a comprehensive optimization of the double reheat system, the heat rate of the optimized system (Case 3) further decreases by 2029.12 kJ/kWh in comparison with that of Case 1.

CONCLUSION

Coal will continue to widely used as fuel for electricity generation. Although Turkey has a rich coal reserves, nature gas is in used to generate almost half of electricity at Turkey. Huge numbers of sub-critic power plants are built at Turkey. The live steam parameters of power plants at Turkey are around and 550 °C [5] and their thermal efficiency are between 30% and 40% [14].They release great ratio of CO_2 and contribute global warming effect. Therefore, optimized double reheat USCPPs are obligation to increase thermal and exergy efficiency and decreases CO_2 emission. This study presents comparative energy and exergy analysis of a power plant with sub-critical, super-critical and ultra-supercritical. In this study, three coal-fired power plants were chosen to indicate improvements of energy and exergy efficiencies. Comparative thermodynamic analyses of the three Cases were conducted. Case 3 which involves four HPRHs, six LPRHs, two desuperheaters and one regenerative turbine has the best results compared with Case 1 and Case 2. Because, Case 3 is operated ultra-supercritical steam conditions and it has ten stage steam extraction to increase final feed water temperature. Moreover, Case 3 has higher energy and exergy efficiency and lower fuel consumption compared to Case 1 and Case 2. The results of this study are shown as follows;

(1) Thermal efficiency of Case 3 increases 9.241 % compared with Case 1.

(2) Exergy efficiency of Case 3 increases 8.06 % compared with Case 1.

(3) Fuel consumption of Case 3 reduces 67.47 kg/s (20%) compared with Case 1. CO_2 emission decreases on account of reducing fuel consumption. Figure 5 shows the comparison of the energy and exergy efficiency of all Cases.

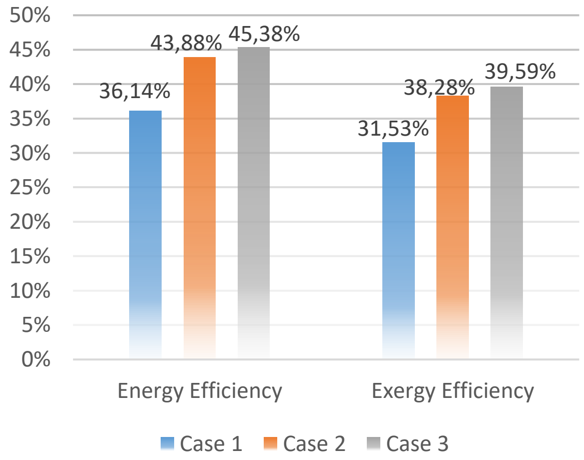

Figure 5. Comparison of the energy and exergy efficiency

Once the efficiency improvement strategy has been applied, it is necessary to take into thermodynamic and economic approach to completely analyses the results. A future suggestion is to study the thermoeconomics of these Cases.

NOMECLATURE

USCPP	Ultra Super-critical Power Plant
HP	High Pressure
IP	Intermediate Pressure

LP	Low Pressure
RH	Regenerative Heater
DEA	Deaerator
GEN	Generator
CON	Condenser
FWP	Feed Water Pump
LHV	Lower Heating Value
η_I	First law efficiency
P_{gen}	Power generation
E_{total}	Total energy input per unit time
q	Heat ratio
φ	Fuel exergy rate of fuel lower heating value
B_0	Fuel exergy value
H_u	Fuel lowering heat value
$B_{0,solid}$	Solid fuel exergy value
w	Moisture rate of fuel
h_{fg}	Evaporation enthalpy of ambient temperature
η_{II}	Second law efficiency
w_{out}	Power output
B_g	Total exergy input of solid fuel

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