Optimization of Reheat–Regenerative Super Critical Rankine Cycle Performance through the Application of Exergy Analysis and Pinch Technique

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Abstract

The objective of this study is to refine Siamak and Majid formulation of combined exergy analysis and pinch technique in order to optimize a super critical reheat–regenerative Siamak and Majid formulation assumes the feedwater heater as an indirect contact heat exchanger whether it is an open feedwater heater (OFWH) or a closed feedwater heater (CFWH) as such that the formulation oversees the effect of OFWH in the analysis. Thus, in this study the OFWH is to be formulated as a direct contact heat exchanger in order to examine the effect of OFWH in the analysis. By specifying the target minimum temperature difference (T_{min}) of 1^{o}C, the exergetic efficiency of the boiler, the turbine, and the open feedwater heater; and the gross 2nd law efficiency of the power plant are 0.29 %,0.01%,1.08%, and 0.16% lower than that of Siamak and Majid approach.

Keyword : Steam power plant ; feedwater network ; Pinch analysis ; Exergy analysis ; Open feedwater heater.

Introduction

The development of a country can be evaluated by many factors. The amount of annual energy usage is evidence indicated the development levels of each country. Because of development, energy demand is increased but energy resource is limited, it cannot response to that demand for long period of time in the future. This problem has led many countries to change their energy policies to ensure that the energy resource is used effectively. The energy conversion technic and energy conversion device become the challenging topic that is carried out by many researchers to find new technic for better used of available energy resources [1].

Amongst of energy conversion process, Steam power plant based on thermodynamic Rankine cycle play important role in conversion of primary energy resource to electricity. The primary thermal resource that use in this kind of power plant can be solid fuel or gaseous fuel such as coal, biomass, MSW and natural gas etc. but there are any other source that can be used as thermal source in steam power plant such as solar, geothermal, nuclear, etc. [2]. According to [3], nearly 45 % of global electricity was generated from coal, 20 % was generated from natural gas and any 15 % was generated from nuclear.

Base on general aspect of thermodynamic, the Reheat-regenerative Rankine cycle has more thermal efficiency than the simple Rankine cycle [4]. The inlet pressure of turbine, inlet temperature, reheat pressure, reheat temperature, extraction pressure, extraction steam flow rate and condenser pressure are main parameter that effect to the efficiency of plant. By changing these parameters to their optimum value, the plant efficiency could be improved [5].

The optimization of plant operation parameters could be done by Exergy and Pinch analysis. The Exergy analysis is use to identify the location, the source, and magnitude of true thermodynamic inefficiencies in power plants [6]. And Pinch analysis has been used to optimize the heat transfer in heat exchanger network by using the heat energy from the stream rather than from external sources [7]. Pinch analysis technique was developed in ETH Zurich and Leeds University since 1970s in order to integrate the network design of heat exchanger [8].

Until nowadays, pinch analysis has been applied for many applications in chemical

process industrial and also in process of power plant. Due to the plenty number of successful application, Pinch analysis has shown the better result with the energy saving [5].
As example Siamak and Majid [10] have optimize the steam power plant by using pinch technique, In those paper the feedwater heater either open feedwater heater (OFWH) and close feedwater heater (CFWH) modeled as close feedwater heater, and so the model neglect the effect of the OFWH in the pinch analysis. So, in this paper the OFWH will be modeled as it is to correct the result of the modeling.

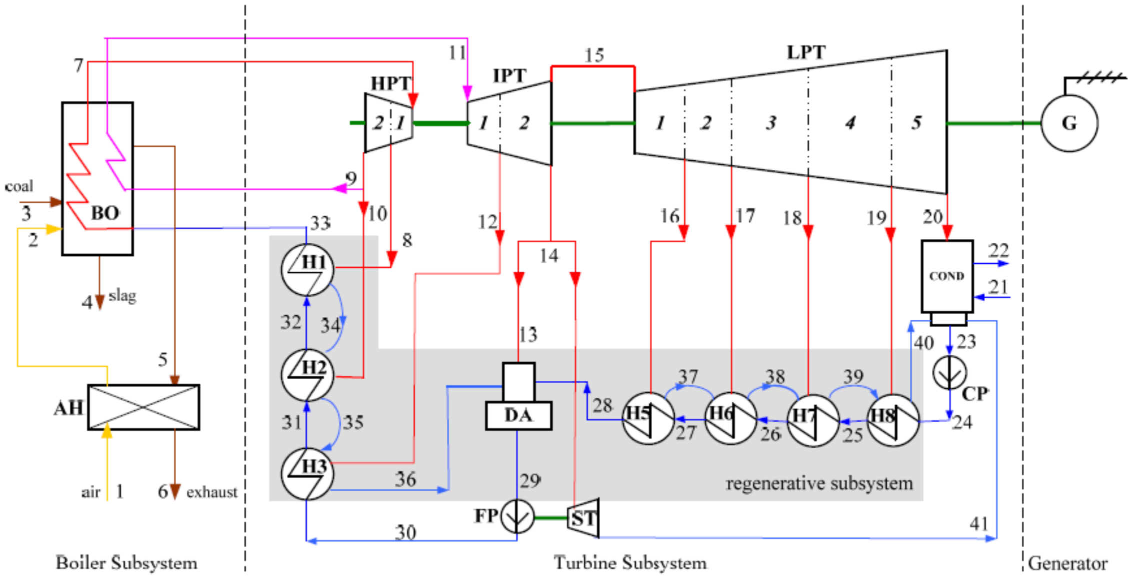


Figure 1 Supercritical power plant diagram. [3]

Plant Description

The plant has power capacity 671 MW consisting of a boiler, turbine, and electrical generator that show in figure 1.
The component are boiler, 2 stage high pressure turbine (HPT1, HPT2), reheater, 2 stage intermediate pressure turbine (IPT1, IPT 2), 5 stages low pressure turbine (LPT1-LPT5), 7 feedwaters heater, condensate pump, boiler feed pump, and deaerator.
The information of this power plant is listed in Table 1.

Table 1 Primary information of 671 MW Supercritical Power Plant

Parameter	Value
Capacity	671 MW
Turbine inlet pressure	254 Bar
Turbine inlet temperature	571 °C
Reheat pressure	41 Bar
Reheat temperature	569 °C
Condenser pressure	0.059 Bar
Main steam flow rate	522.2 kg/s

Table 1 Primary information of 671 MW Supercritical Power Plant (Cont.)

Parameter	Value
Efficiency (%)	48.22
PP efficiency (%)	45.1
Boiler Efficiency (%)	92.81
Isentropic Eff (%)	
HPT	88
IPT	92
LPT (1-3)	94
LPT (4-5)	78

Method

In [10], OFWH is modeled as CFWH with 0°C pinch point temperature, so the streams at the process assumed not mixing. But the real process in OFWH is mixing of the hot stream and cold stream and producing the same outlet temperature of hot stream and cold stream. Based on these information OFWH can be modeled as parallel flow direct heat exchanger as shown as Figure 2.

The energy balance for direct contact heat exchanger can be used to calculate the OFWH process as equation 1 and 2

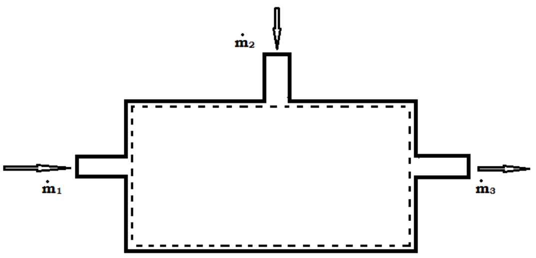


Figure 2 Direct contact HE

$$E_{in} = E_{out} \quad (1)$$

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = (\dot{m}_1 + \dot{m}_2) h_3 \quad (2)$$

So in this deaerator model, the steam bleed extraction and the feedwater are mixing.

Exergy Analysis

Exergy is the maximum theoretical work obtainable from an overall system consisting of a system and the environment as the system comes into equilibrium with the environment (passes to the dead state) [9]. The purpose of Exergy analysis is to identify the location, the magnitude, and the sources of thermodynamic inefficiencies in a thermal system.

The specific exergy flow of a fluid at any cycle state is given by Equation 3:

$$e = (h - h_o) - T_o(s - s_o) \quad (3)$$

The reversible work as a fluid goes from an inlet state to an exit state is given by the exergy change between these two states, as follow:

$$e_o - e_i = (h_o - h_i) - T_o(s_o - s_i) \quad (4)$$

The exergy loss and exergy efficiency for each of the Rankine cycle components can be calculate using equation 4.

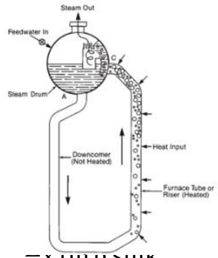
Table 2 show the calculation of exergy destruction and exergetic efficiency in each component of the power plant

Pinch Technique

Pinch technique is used to optimizing the process to process heat recovery and reducing external utility loads in process plant. By using this Pinch analysis the entropy generations at heat exchanger network will reduced and the Minimum Energy Requirement (MER) of the process is acquired. To using pinch technique, Composite Curve (CC) are used as tools for pinch technique. Composite Curve is representing the hot stream and cold stream heat load as a function of enthalpy (kW) against temperature (°C) as showed in figure 3. The overlap between the cold stream and hot

Table 2. Exergetic efficiency and exergy destruction of boiler, condenser, turbine, feedwater heaters network, and the overall steam cycle. [10]

Boiler

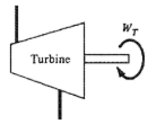


$$eff_b = \dot{E}_{x\,b\,sink}/\dot{E}_{x\,turb\,source} \times 100$$

$$\dot{E}_{x\,destruction\,b} = \dot{E}_{x\,b\,source} - \dot{E}_{x\,b\,sink} \quad ; \quad \dot{E}_{x\,b\,source} = \dot{m}_f \times hv_{ava}$$

$$\dot{E}_{x\,b\,sink} = \dot{m}_{main} \times (e_{x\,main} - e_{x\,in\,b}) + \sum_{i=1}^{m} \dot{m}_{rh\,i} \times (e_{x\,hot\,rh\,i} - e_{x\,cold\,rh\,i})$$

Turbine

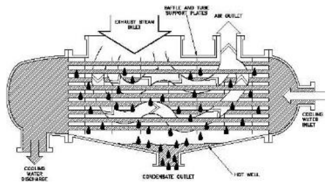


$$eff_{turb} = \dot{W}_{out\,turb}/\dot{E}_{x\,turb\,source} \times 100 \quad ; \quad \dot{E}_{x\,destruction\,turb} = \dot{E}_{x\,turb\,source} - \dot{E}_{x\,turb\,sink}$$

$$\dot{E}_{x\,turb\,source} = \sum_{i=1}^{n} \dot{m}_{ext\,i} \times (e_{x\,main} - e_{x\,ext\,i}) + \sum_{i=1}^{m} \dot{m}_{rh\,i} \times (e_{x\,hot\,rh\,i} - e_{x\,cold\,rh\,i}) + \dot{m}_{out\,turb} \times (e_{x\,main} - e_{x\,out\,turb})$$

$$\dot{E}_{x\,turb\,sink} = \dot{W}_{out\,turb}$$

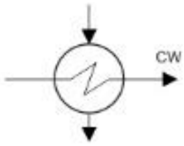
Condenser



$$\dot{E}_{x\,destruction\,c} = \dot{E}_{x\,c\,source} - \dot{E}_{x\,c\,sink} \quad (\dot{E}_{x\,c\,sink} = 0 \text{ and } eff_c = 0)$$

$$\dot{E}_{x\,c\,source} = \dot{m}_{out\,turb} \times (e_{x\,out\,turb} - e_{x\,out\,c}) + \dot{m}_d \times (e_{x\,d} - e_{x\,out\,c})$$

Feedwater heater network



$$eff_h = \dot{E}_{x\,h\,sink}/\dot{E}_{x\,h\,source} \times 100$$

$$\dot{E}_{x\,destruction\,h} = \dot{E}_{x\,h\,source} - \dot{E}_{x\,h\,sink}$$

$$\dot{E}_{x\,h\,source} = \sum_{i=1}^{n} \dot{m}_{ext\,i} \times (e_{x\,ext\,i} - e_{x\,amb}) - \dot{m}_d \times (e_{x\,d} - e_{x\,amb}) + \dot{W}_{pumps}$$

$$\dot{E}_{x\,h\,sink} = \dot{m}_{main} \times (e_{x\,in\,b} - e_{x\,amb}) - (\dot{m}_{out\,turb} + \dot{m}_d) \times (e_{x\,out\,c} - e_{x\,amb})$$

Overall stream power plant

$$\dot{E}_{x\,destruction\,plant} = \dot{E}_{x\,destruction\,b} + \dot{E}_{x\,destruction\,turb} + \dot{E}_{x\,destruction\,c} + \dot{E}_{x\,destruction\,h}$$

$$eff_{2nd\,law,gross,cycle} = \dot{W}_{out\,turb}/(\dot{m}_f hv_{ava}) \times 100$$

stream are the heat recovery potential and by bringing the pinch closer it will reduce the hot utility, cold utility or external heating required

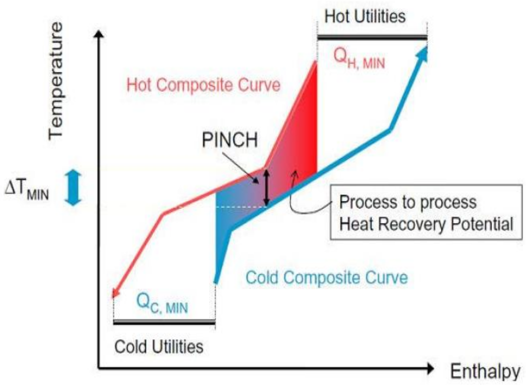


Figure 3 Composite Curve [5]

Modelling OFWH

In [10] OFWH is modeled as CFWH with 0°C pinch point temperature, so the streams at the process not mixing. But the real process of OFWH is mixing of the hot stream and cold stream and produce the same outlet temperature of hot stream and cold stream as shown in figure 4 and 5. Based on the information from figure 4 and 5. OFWH can modeled as parallel flow direct heat exchanger.

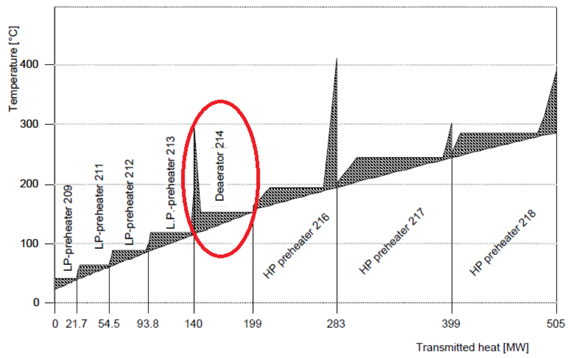


Figure 4 Composite curve of steam power plant [12]

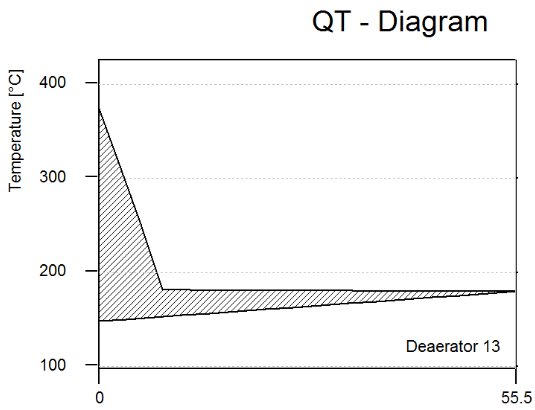


Figure 5 Composite curve of deaerator.

In order to reach the target pinch temperature, change of the mass flow of the stream is necessary. To calculate the mass flow needed to reach the target pinch point temperature, energy balance is applied between 2 pinch point temperature by using equation 5

$$\sum_i m_i . c_{pi} . \Delta T_i - \sum_j m_j c_{pj} \Delta T_j = 0 \qquad (5)$$

After solving the energy equation, mass flow of each extracted turbine are determined. The effect of this new mass flow will known by using exergetic efficieny and exergy destruction in each component. Mass flow required for 1°C pinch point targeting. are shown in table 3. OFWH means the refined model in this paper and CFWH is the previous model.

The sudden change happen at extraction steam number 4 which is located at deaerator, because the direct mixing of extraction steam and feedwater happen at OFWH.

Table 3 Mass flow each stream before and after modification

Stream	Mass flow	
	OFWH	CFWH
FW cond daer	391.98	390.53
FWdaer boiler	530.00	528.50
Steam reheater	444.78	447.16
Ex 1	39.05	38.05
Ex 2	46.17	43.28
Ex 3	29.00	28.65
Ex 4	23.80	27.97
Ex 5	26.42	27.83
Ex 6	13.07	13.07
Ex 7	16.95	16.94
Ex 8	14.50	8.48
Cond	292.33	295.48

Analysis

Figure 6 (a) and (b) are composite curve of OFWH model and the previous model with T_{min} targeted is 1°C. Remember that lowering the pinch point will have trade off or consequence such as more capital cost because need more area for the heat exchanger.

From figure 6a and b the difference happen at pinch point that are marked with black circle in the figure, which is the OFWH. In figure 4a there are no significant temperature change compared to figure 3b.

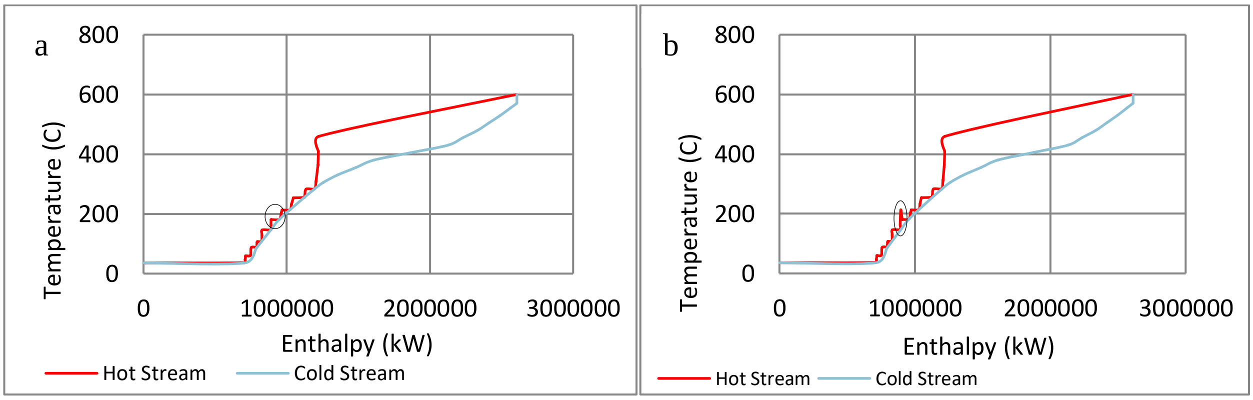


Figure 6 Composite Curve Diagram: (a) OFWH modeled as CFWH and (b) OFWH modeled as OFWH

Result

From table 4 there are 3 case for the power plant not modify, OFWH, and CFWH. Not modifiy means the current power plant,

OFWH means after optimized with pinch technique and modeled OFWH as OFWH, and CFWH are the previous model which is OFWH asummed as CFWH.

Both pinch target temperature for both OFWH and CFWH is 1°C. The both model can reduce the entropy generation in each component, so increasing the exergetic efficiency of each component. And so the gross 2nd law efficiency of the plant.

Table 4 Parameter of power plant before and after optimized

Item	Unit	Model		
		Not Modify	OFWH	CFWH
Exergy destruction in boiler	MW	730.99	719.58	696.24
Boiler exergetic efficiency	%	51.67	53.00	53.29
Exergy destruction in turbine	MW	49.69	49.31	49.13
Turbine exergetic efficiency	%	93.28	93.28	93.28
Exergy destruction in condenser	MW	26.64	26.25	25.95
Exergy destruction in the feedwater heaters network	MW	16.81	11.36	9.14
Feedwater heaters network exergetic efficiency	%	91.54	94.21	95.29
Cycle gross 2nd law efficiency	%	45.10	45.60	45.76
Specific fuel consumption	g/kWh	363.18	359.19	357.93
Fuel consumption (per unit)	kg/s	68.80	68.05	67.81
Rankine cycle efficiency	%	45.10	45.64	45.75

Conclusion

By comparing the result for OFWH and CFWH modeling, the result from CFWH modeling is better, show by increase in the exergetic efficiency of boiler, turbine, feedwater, and cycle gross 2nd law efficiency. OFWH modeling is lower because there are mixing in the process that make more entropy generation and the high temperature difference in stream in OFWH, so the exergy destruction in feedwater network increase and impact to another component such as boiler and turbine.
The difference between OFWH and CFWH in exergetic efficiency of boiler is by 0.29 %, turbine 0.01 %, feedwater 1.08 %, cycle gross 2nd law efficiency by 0.16 % and Rankine cycle efficiency by 0.11% for pinch target 1°C.
By using the pinch technique, the exergy destruction for each subsystem is lowered, and have potential to reduce the fuel consumption by $28x10^6$ kg, cost saving for fuel are $427.968 each year, and reduction of green house gas emission about 6.163.200 tons for 8000 operating hours

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