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Energy and Exergy Analysis of the Steam Power Plant Based On Effect the Numbers of Feed Water Heater

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Mohammed Kamil Mohammed[1], Wadhah Hussein Al Doori[2], Ataalah Hussain Jassim[2], Thamir Khalil Ibrahim[2,*], Ahmed Tawfeeq Al-Sammarraie[3]

[1] Department of Mechanical and Nuclear Engineering, University of Sharjah, United Arab Emirates
[2] Department of Mechanical Engineering, Tikrit University, Tikrit, Iraq
[3] Department of Mechanical Engineering, University of California, Riverside, CA 92521, USA

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ABSTRACT

This study involved the performance of energy and exergy analysis on a 200 MW Steam cycle power plant (SCPP). The aim is to investigate the effect of using different number of feed water heaters (FWHs) on the cycle performance. Several simulation analyses were conducted in this study on a MATLAB platform. The computer model used was based on natural gas combustion, enthalpy balances, energy balances, and entropy changes of the SCPP. The real case study was simulated on a validated model of the SCPP for Shahid Montazeri Power Plant. The exergy destroyed within each components system and the exergy efficiency are determined to study the irreversibility of the system and identify the chances for the enhancement of the power system. Based on the result of the analyses, the energy and exergy efficiencies of the SCPP were determined to be about 37.52 % and 41.7 %, respectively. In the SCPPs, the combustion chamber (boiler) contributes the highest exergy destruction rate (around 48 % of the exergy value of the gas) among the main components of the power system.

Keywords:
Steam Cycle, Energy, Exergy, Irreversibilities, Feed water heater

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1. Introduction

Most of the power generation systems are designed and implemented based on the First Law of Thermodynamics, which indicates that only the energetic criteria are taken into account [1-5]. However, the actual useful energy loss must include the exergetic criteria to obtain both the quality and quantity of energy [6-10]. Hence, thermodynamics analysis of power plants performance has to be done energetically and exegetically to determine more accurate data and results. Recently, the evaluation of the performance of power plants has been moved towards the Second Law of Thermodynamics, which focus on exergy. According to previous studies, this method not only evaluates, but also optimizes and suggests improvements to be made on the power plant to achieve a better performance [11-14]. Steam power plants have been introduced since the 20th century as

* *Corresponding author.*
E-mail address: thamirmathcad@yahoo.com (Thamir Khalil Ibrahim)

steam turbine power plants at first for the generation of electricity [15-19]. 20There are few design patents and various auxiliary equipment supporting the system [20-25]. Steam power plants mainly consist of a de-aerating feed water tank, a high-pressure steam turbine, a high-pressure steam boiler, a low-pressure steam turbine, and a water-cool condenser connected in series in a closed circuit [4, 26,27]. The function of the feed water tank is to remove air from the water before it flows into the steam boiler. Moreover, a steam jet is installed between the low-pressure steam turbine and the condenser for the movement of steam from the turbine to the condenser for cooling processes [28, 29]. On the other hand, the condensate from the condenser is pumped by a steam jet pump to enter the feed water tank [30,31].

The feed water heater (FWH) is a component of the power plant which serve as a water preheater before it flows into the boiler to generate steam. This preheating process is expected to reduce the irreversibilities that occur in steam generation and thus, improves the thermodynamic efficiency of the system. The performance of the simulation model of a power unit depends on the design of the components. As per previous studies, there are few problems (such as first, the high installation cost of the sample steam power plant [32] and second, the temperature of feed water entering the boiler [33-38], and third, the thermodynamics analysis based on first law of thermodynamics is not enough to explain the efficiency and energy loss of the engineering system encountered in the SCPPs [39-41]. The aim of this study is to determine the effect of different numbers of feed water heaters on the performance of the SCPP. Thermodynamic analysis was conducted to determine the performance of the SCPP based on energy and exergy analyses, excluding aerodynamics and fluid flow. The operational parameters included in the analysis are the temperatures of the feed water, steam turbine temperature, pressure level, steam mass extraction, and fuel heating value.

2. Plant Description

The SCPP of Shahid Montazeri is located in the Northwest of Isfahan–Tehran highway. It consists of eight units, each with a 200 MW capacity. Table 1 shows the technical specifications of this power plant. The Rankine cycle represent the heat cycle of a power plant; the heat process of this plant is briefly depicted in Figure 1.

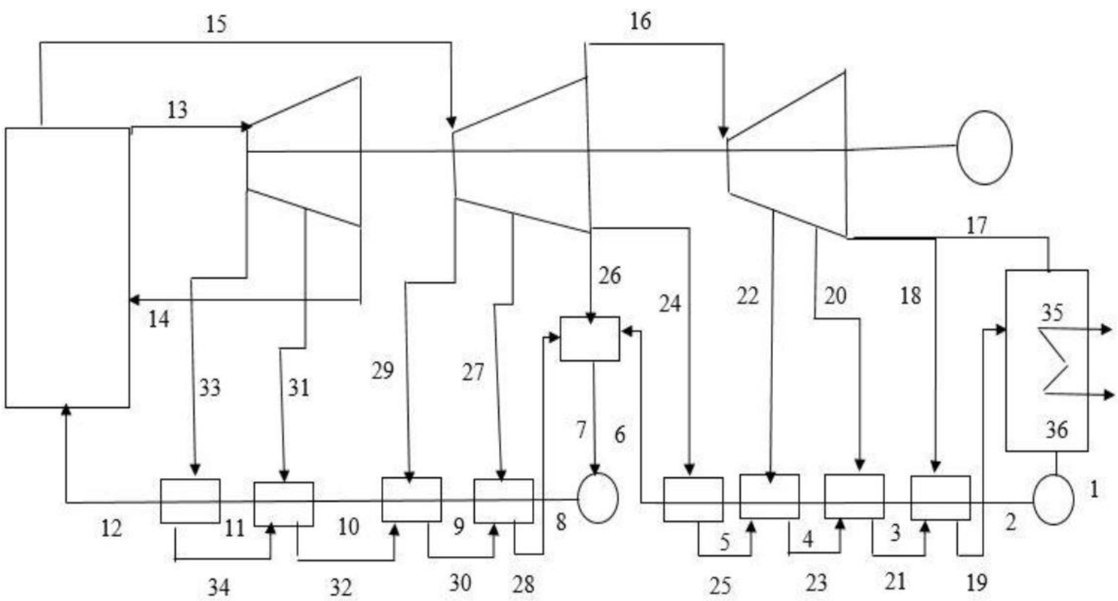

Fig. 1. Schematic diagram with 9th FWH

Table 1
Operating condition of the power plant

Operation Condition	Value	Units
Generated power	200	MW
Consumption power	14	MW
Fuel Mass flow rate	54	Nm^3/h
Heat rate	10448.6	KJ/kW.h
Total steam flow rate	670	Ton/h
High pressure of the steam	130	Bar
High temperature of the steam	540	ºC
Temperature of the water inlet to the boiler	247	ºC
Temperature of the stack gases	160	ºC
Volumetric flow rate of the Inlet gas to the burners	9.6×10^6	Nm^3/h
Draft fans Number per unit	2	-
burners Number	12	-
Efficiency of combined pumps and motors	95	%

3. Thermodynamics Analysis

During the energy analysis, the balance equations developed is reliant on the first thermodynamic law. For the individual components of the power plant, mass and energy balances are expressed under a steady-state condition. Continuity equation [42-44]

$$\sum_i \dot{m} = \sum_e \dot{m} \tag{1}$$

Energy equation [45-47]

$$\dot{Q}_{in} + \sum_i \dot{m}\, h = \dot{w}_{output} + \sum_e \dot{m}\, h \tag{2}$$

In the equations above, the mass flow rate, enthalpy, work output, and heat input are indicated as $\dot{m}$, h, $\dot{W}_{output}$, and *in*, respectively. Generally, heat input depends on the fuel used in power plants. In this case, it is expressed as

$$\dot{Q}_{in} = \dot{m}_{fuel} \cdot \overline{HHV}_{fuel} \tag{3}$$

where fuel used is natural gas with 48806 kJ/kg. The power output of a steam power plant is determined by the work produced by the steam turbines [35].

$$\dot{w}_{ST} = \eta_{ST}[\dot{m}_i(h_i - h_1) + (\dot{m}_i - \dot{m}_1)(h_1 - h_2) + (\dot{m}_i - \dot{m}_1 - \cdots - \dot{m}_n)(h_n - h_e)] \tag{4}$$

Eq. (4) is dependent on the number of steam turbines installed in the steam power plant.

The subscripts 1, 2 …n refer to the number of steam extraction in the steam turbines. For this case study, we assume that the only internal power consumption component is the pump used to deliver the condensate and feed water. The equation involved is:

$$\dot{w}_{pump} = \frac{\dot{m}(h_e - h_i)}{\eta_{pump}} \tag{5}$$

Similar to steam turbines, the pump efficiency is considered in the calculation to obtain more accurate results. Thus, we can define the net electrical power output of the steam turbine by [1, 48-50]

$$\dot{w}_{net} = \sum \dot{w}_{ST} - \sum \dot{w}_{pump} \tag{6}$$

Exergy can be divided into four focuses, consisting of physical, chemical, potential and kinetic exergies. Physical exergy demonstrates the maximum work capability of a particular system at the initial conditions (T_o). Meanwhile, chemical exergy is related to the changes in the systems' chemical composition from the equilibrium conditions. Chemical exergy is determined from the combustion reactions process. A combination of the first and second thermodynamic laws will be expressed as [51]

$$\dot{E}_{x,heat} + \sum_i \dot{m}_i e_{x,i} = \sum_e \dot{m}_e e_{x,e} + \dot{E}_{x,w} + i_{dest.} \tag{7}$$

$$\dot{E}_{x,heat} = \left(1 - \frac{T_\circ}{T_i}\right) \dot{Q}_i \tag{8}$$

$$\dot{E}_{x,w} = w_{output} \tag{9}$$

$$e_x = e_{x,physical} + e_{x,chemical} \tag{10}$$

where T represents the absolute measured temperature (K) while *i, e* and 0 are the inlet, outlet and ambient conditions, respectively. $\dot{E}_{x,heat}$ is calculated from the exergy flow associated with heat transfer. Contrarily, $\dot{E}_{x,W}$ represents the exergy flow associated with the work done by the system.

3.1 Physical Exergy

The equation below is used to calculate the physical exergy of water/steam phases.

$$e_{x,physical} = (h - h_\circ) - T_\circ(s - s_\circ) \tag{11}$$

Eq. (11) is used to determine the physical exergy of water/steam flowing in the power plant; it involves the enthalpy, h_o, and entropy values of the system under environmental condition. For ideal gases, physical exergy is further divided into temperature and pressure terms as shown in the equation below [52, 53].

$$e_{x,physical} = e_x^T + e_x^p \tag{12}$$

$$e_x^T = c_p \left[(T - T_\circ) - T_\circ \ln \frac{T}{T_\circ}\right] \tag{13}$$

$$e_x^p = RT_\circ \ln \frac{p}{p_\circ} \tag{14}$$

3.2 Chemical Exergy

Chemical exergy can be calculated by the molar composition, y_k, and standard molar chemical exergy of the combustion product ($ex_k^{chemical}$) after the burning process. The subscript *k* refers to the type of gas contained in the gas mixture produced. Gases produced from combustion are assumed as ideal gas mixtures during exergy analysis [6, 7]. Hence, it is necessary that when determining the chemical exergy of a gas mixture, its molar composition should be considered after the combustion process.

$$ex^{chemical} = \sum_{k=1}^{n} y_k ex_k^{chemical} + RT_{\circ} \sum_{k=1}^{n} y_k \ln y_k + G^E \tag{15}$$

The term G^E is known as the excess free Gibbs energy. At low pressure conditions, it is negligible for gas mixtures. The gas constant R used in the calculation of the chemical exergy of combustion gases is 8.314 $JK^{-1}mol^{-1}$. Besides that, by using Eq. 16

$$\xi = \frac{e_{x,fuel}}{LHV_{fuel}} \tag{16}$$

It can be determined as the chemical exergy of fuel, where the term ξ is the ratio of the chemical exergy of the fuel, $ex_{,fuel}$ is the heating value of fuel (LHV_{fuel}). As earlier stated, we used natural gas in this analysis; in fact, most of the gaseous fuel has the ratio of chemical exergy to the lower heating value close to 1 [54]. Thus, the value of ξ for natural gas is taken as 1.06. Since ambient condition varies at different locations and timeframe, it is necessary to identify them before carrying out the exergy analysis [55]. In this case, the environmental temperature and pressure were assumed as 298 K and 101.3 kPa. Table 2 presents the reference ambient model for air used in the current analysis.

Table 2
Chemical exergy and mole fractions of the components of the air

Combustion	Mole Fraction	Standard Molar Chemical Exergy (kJ/mol)
O_2	0.2034	3.97
CO_2	0.0003	19.87
H_2O	0.0303	9.49
N_2	0.7567	0.72

Based on previous studies, usually, in steam power plants, the exergy of steam is determined at all states of points. The exergy changes are determined for every major component, such as the boiler, turbines, condenser, etc. The rate of exergy destruction and exergy efficiency is calculated to determine the main source of the loss in the operating system [56, 57].

3.3 Exergy Destruction Rate

Boiler

$$\dot{E}_{D,B} = \dot{E}_f + \dot{E}_{x,i} - \dot{E}_{x,e} \tag{17}$$

Steam turbine

$$\dot{E}_{D,ST} = \sum_{in}^{n} \dot{E}_{x,i} - \sum_{out}^{n} \dot{E}_{x,e} - \dot{w}_{output} \tag{18}$$

Pump

$$\dot{E}_{D,p} = \dot{E}_{x,i} - \dot{E}_{x,e} + \dot{w}_{pump} \quad (19)$$

Feed water heater

$$\dot{E}_{D,H} = \sum_{in}^{n} \dot{E}_{n,i} - \sum_{out}^{n} \dot{E}_{x,e} \quad (20)$$

Condenser

$$\dot{E}_{D,Cond.} = \dot{E}_{x,i} - \dot{E}_{x,e} - \sum_{k=1}^{n} \left(1 - \frac{T_{\circ}}{T_k}\right) \dot{Q}_k \quad (21)$$

3.4 Exergy Efficiency

Boiler

$$\eta_{x,B} = 1 - \frac{\dot{E}_{D,ST}}{\dot{E}_f} \quad (22)$$

Steam turbine

$$\eta_{x,ST} = 1 - \frac{\dot{E}_{D,ST}}{\dot{E}_{x,i} - \dot{E}_{x,e}} \quad (23)$$

Pump

$$\eta_{x,p} = 1 - \frac{\dot{E}_{D,pump}}{\dot{w}_{pump}} \quad (24)$$

Feed water heater

$$\eta_{x,H} = 1 - \frac{\dot{E}_{D,H}}{\sum_{in}^{n} \dot{E}_{x,i}} \quad (25)$$

Condenser

$$\eta_{x,Cond.} = 1 - \frac{\dot{E}_{D,Cond.}}{\dot{E}_{x,i} - \dot{E}_{x,e}} \quad (26)$$

4. Result and Discussion

The figures illustrate the results of the current analysis during this study. For each energy and exergy analyses, the results of the calculation exploited the mathematical model built in this study. Besides that, they are diagrammatically represented to provide a clearer view of the link between the parameters in power cycle. The performance of steam cycle power plants is mentioned and studied beneath the first and second law of thermodynamic. The impact of different operational parameters on the performance of the facility plant is investigated and discussed for optimum operational conditions. The thermal efficiency of Montazeri Steam power plant was determined for steam cycles to account for the development due to the implementation of a steam cycle facility.

Several comparisons have been made between the calculated values and therefore, the information obtained from the facility station considered the deviation of the experimental values from the theoretical values.

The effects of reheat pressure, boiler pressure, temperature of flue gases, and turbine inlet temperature on the performance of cycle have been parametrically studied and a specific range of Feed Water Heaters (FWHs) has been specified. The effect of the level of heat pressure increase on the exergy efficiency of the SCPP is presented in Figure 2. The magnitude of the reheat steam pressure varies from 0.1 to 0.9 in relation to the boiler pressure. The turbines' work output and the heat input to the boiler reduces as the reheat pressure increases; hence, the plant experiences maximum efficiency at the optimum reheat pressure.

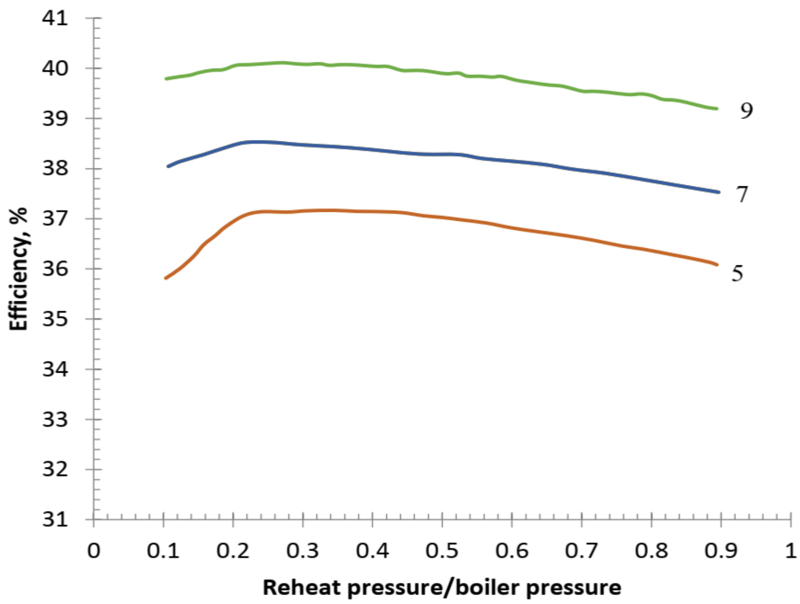

Fig. 2. Effect of number of FWHs with reheat pressure on exergy efficiency

An increase in the number heaters will increase the exergy efficiency of the system. The systems' reheat pressure is maximum at about 20-25 % of the maximum boiler pressure. Figure 3 depicts the outcome of the magnitude of reheat pressure in relation to the entire exergetic loss within the boiler. There was an initial decrease in the entire boiler exergetic loss but as the heat up pressure increases, the exergetic loss similarly increased as shown Figure 3. The incorporation of heaters reduces the boilers' exergetic loss because of the small temperature difference between the water/steam and the flue gases.

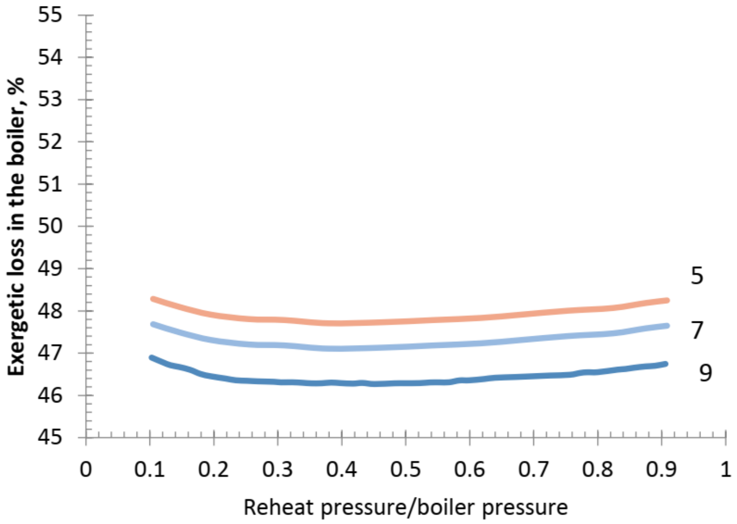

Fig. 3. Effect of number of FWHs with reheat pressure on exergetic loss in boiler

The influence of the boiler pressure and the number of FWHs on the exergy efficiency of SCPP is depicted in Figure 4. An increase in the boiler temperature and the number of FWHs increased the efficiency of the system. Although there was an increase in the exergy efficiency with increase in the number of heaters, it is not advisable to use the optimum number of additional FWHs as it will not have a significant improvement on the potency of the cycle. An increase in the boiler pressure to 160 bar (with the addition of the initial FWH) increased the exergy efficiency from 34% to 37%.

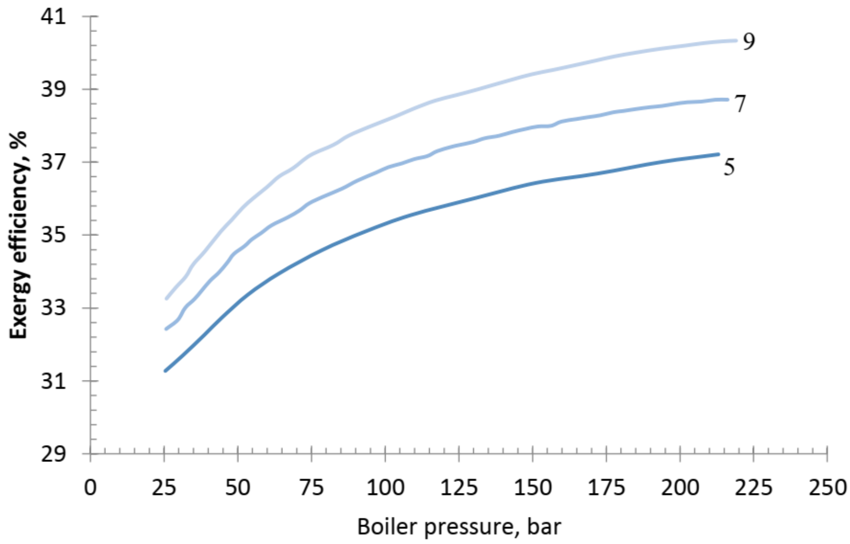

Fig. 4. Effect of boiler pressures with number of FWHs on exergy efficiency

The result of different numbers of FWHs and turbine inlet temperatures on the exergy efficiency of SCPP is given in Figure 5. The increases in the turbine inlet temperature and the number of FWHs increased the exergy efficiency. The steam heat content at the inlet of the turbine was increased with an increase in the water temperature at a set pressure. The increase in the work output (the cycle efficiency) was due to the increased steam temperature and pressure. The effect of temperature on the cycle efficiency is quite dependent on the pressure. The cycle efficiency of energy and exergy increased by increasing the number of FWHs as shown in Figure 6. The energy and exergy with the

5th FWH were 33.24 and 37.35, respectively. With the 7th FWH, they were 35.81 and 39.6 respectively, while the 9th FWH showed 37.52 and 41.7 energy and exergy efficiencies, respectively.

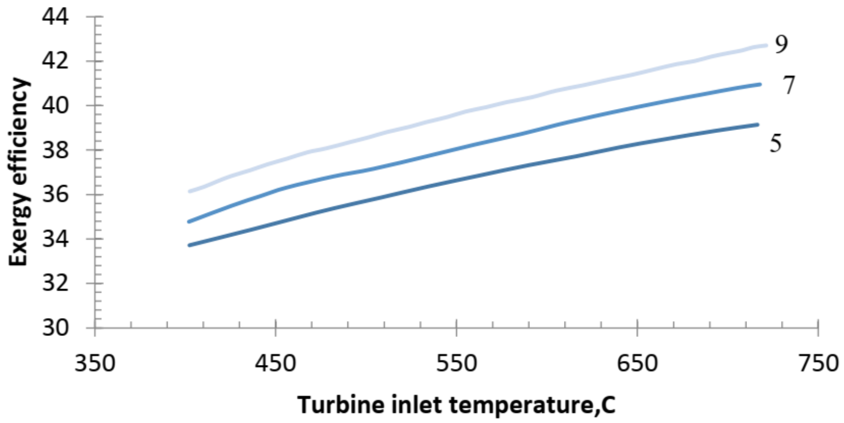

Fig. 5. Effect of turbine inlet temperatures with number of FWHs on the exergy efficiency.

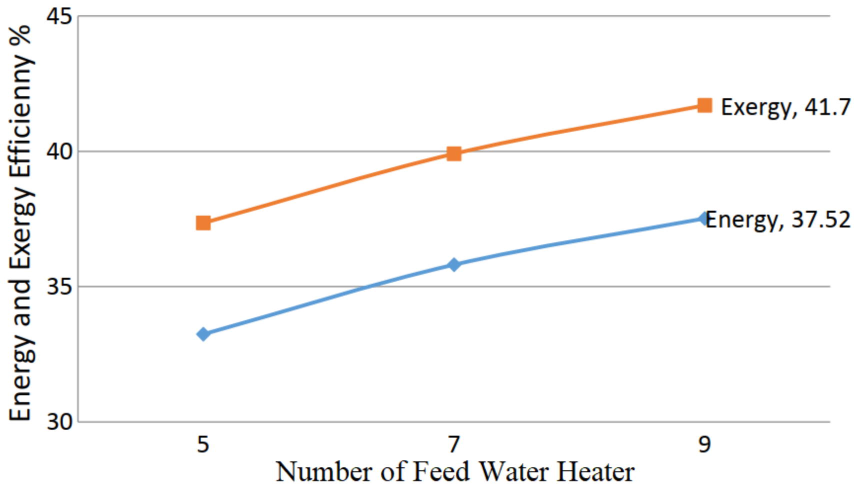

Fig. 6. Thermal Efficiency of the Cycle

5. Conclusion

In this study, a steam cycle power plant with different numbers of FWHs was investigated via energy and exergy analyses. The selected case study was discussed and applied via a general methodology that involved the use of mass balanced equation, energy balanced equation, and entropy generation balanced equation. First, the case study proposed by the author was discussed; the results of the analyses were presented in graphs. Additionally, the optimum number of FWHs was selected to be 9 since more heaters will increase the boiler temperature and decrease the amount of fuel consumed in the boiler. Energy and exergy analyses were carried out for a 200 MW steam cycle power plant (Mohammad Montazeri power cycle). By implementing the steam cycle, the thermal efficiency of this power plant can reach 40.1 % with the addition of 130 MW work done by the steam turbine. The energy loss of the condenser accounts for about 70% of the total energy losses in the SCPP whereas the energy loss of the boiler is about 10 % of the total energy lost. However, the analysis of SCPP based on exergy can identify the component that has the most rate of exergy utilization. In this case, the major exergy utilization was found to occur in the boiler mainly due to the fuel combustion process and the heat transfer between two widely different temperatures.

Hence, the performance of the plant can be improved by reducing the exergy utilized in these components for priority. From a thermodynamics point of view, clearly, the opportunity for a remarkable enhancement presents in the boiler; thus, the boiler is worth the efforts towards reducing the losses. The exergy efficiency of the overall power cycle was however determined to be 40.3 % from the exergy analysis.

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