Providing the New Energy-Exergy-Water Nexus Based Strategy for a Petrochemical Unit

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Abstract

The increasing population growth and industrial development have led to increasing electricity demand, greenhouse gas emissions, and water consumption. On the other hand, climate change can influence the amount of available renewable water. In this article, part of the steam cycle of Petrochemical Unit A has been modeled, analyzed, and reviewed. Scenarios and suggestions for saving steam and energy consumption have also been presented, and the amount of savings for these scenarios has been calculated economically, considering the rates of the desired utilities. For this purpose, the engineering equation solver (EES) software is used. The mass balance of the intended steam cycle is first carried out and then the required parameters, such as efficiency, exergy, power, etc., of different equipment are calculated. Finally, by providing solutions and scenarios, the assessment of the optimization of water and energy in the steam cycle of Petrochemical Unit A is dealt with. By implementing scenarios for a condensing steam turbine named the STC-3001 turbine, the amount of steam consumption is reduced by 1.5 to 10.7 tons/hour, equivalent to an annual savings of $210,000 to $1,433,507 according to the intended utilities. Furthermore, by improving the steam system of the STC-1001 gland turbine, the amount of its steam consumption is reduced by about 6 tons/hour, equivalent to an annual savings of $778,400.

Keywords: water-energy nexus, steam cycle, steam producer and consumer, improving water and energy consumption, petrochemical unit

Nomenclature

Abbreviations

HHP	High High Pressure
HP	High Pressure
LP	Low Pressure
LHV	Low Heating Value
ST	Steam Turbine

Latin symbols

$\dot{m}$	Mass Flow Rate (t/h)
$\dot{m}_f$	Fuel Mass Flow Rate (t/h)
P	Pressure (bar)
T	Temperature (℃)
I	Exergy Destruction (kW)
Ex	Exergy
H	Enthalpy (kJ)
S	Entropy (J/K)
W	Work (kJ)

Greek symbols

Ψ	Physical Exergy
η_{th}	Thermal Efficiency
η_{exergy}	Exergy Efficiency
γ_f	Exergy Factor

Subscripts

a	Actual
s	Isentropic
i	Inlet
o	Outlet
P	Pump
T	Turbine
f	Fuel

1. Introduction

Water and energy resources are inseparably intertwined and interdependent because large amounts of energy are needed for water pumping, filtering, transferring, heating, cooling, and recycling, while water is used for power generation as steam to rotate turbine blades and primary coolant in thermal power plants [1]. During the last decade, the analysis of issues concerning the water-energy nexus has become an issue to increase scientific and political communities' attention. The rapid growth of cities and population, along with the global economic development, imposes heavy pressure on the limited resources on our planet, including water, energy, food, land, and ecosystems. Water and energy saving is becoming one of the most crucial prerequisites for sustainable development all around the world [2]. Industrial water consumption possesses a considerable share in the global consumption per year, consuming 19% of the annual water withdrawal [3]. Global warming and climate changes have led the shortage of water resources to reach a critical level. Based on estimates, 34 countries experience water stress with a percentage of approximately 25%-75%, while 25 countries, including Iran, have a water stress of above 75% [4]. O. R. Altarawneh et al. evaluated a combined cycle power plant (CHP) in Jordan to identify the locations and devices with the highest energy losses due to high irreversibility, which led to a reduction in the plant's performance. The aim of this study was to help improve the plant's performance by pinpointing areas with significant energy losses and proposing a solution to eliminate them [5]. M.H. Hamayun et al. studied a steam power plant based on energy and exergy analysis. Their analysis indicated that the boiler is the primary source of exergy destruction due to incomplete combustion process and inadequate insulation. Additionally, the exergy efficiency (%) and the rate of exergy destruction (kW) of the equipment in the power plant have been calculated [6]. A. G. Celik et al. studied a 210 MW coal-fired thermal power plant in Turkey based on real operational data at various ambient temperatures. An exergy analysis and an exergy-based sustainability assessment were presented. The results of the energy analysis revealed that 59.01% of the total exergy destruction was associated with the boiler, while 29.12% was related to the intermediate-pressure turbine. The findings of this study can lead to more effective decisions regarding the design of future thermal power plants for investors and researchers [7]. M. Tontu et al. compared and investigated three different steam power plants operating under supercritical, supercritical, and subcritical conditions. Energy and exergy determinations carried out to define the performance of each system and the efficiency of the basic equipment. The total efficiency of the power plants was compared. According to the results obtained, higher overall exergy efficiency was found in the supercritical cycle due to lower coal consumption. The energy efficiencies of the subcritical, supercritical and ultra-critical thermal power plants were determined to be 41.5%, 43.8% and 46.0%, respectively. Also, the comparable exergy efficiency values of the thermal power plants were determined to be 39.1%, 40.8% and 41.9%, respectively [8].

M. Mohseni et al. conducted a study to optimizing electricity production in a thermal power plant in Iran by replacing the existing boiler with a heat recovery steam generator. A comprehensive analysis of the existing steam cycle revealed that the boiler, turbine, and condenser had the highest rates of exergy destruction. Six heaters and the boilers provided 25% and 70% of the turbine's input energy, respectively. The analysis of the combined cycle showed that the first-law and second-law efficiencies was increased by 27% and 26%, respectively [9]. U. G. Azubuike et al. investigated the exergy performance of a 200 MW gas-fired steam turbine power plant under full and partial loads. The exergy efficiency of the boiler, compared to other components, showed the lowest values of 42.8%, 42.5%, and 41.8% at 100%, 75%, and 50% loads, respectively. Additionally, the exergy efficiency of the condenser at 25% load exhibited the lowest value (40.29%). Their research provided a ranking of the exergy performance of the power plant components [10].

M. Galal et al. studied the exergy and energy analysis of a steam cycle in a sulfuric acid unit. In this study, a mathematical model was developed using EES software to perform the calculations. The key sources of exergy destruction were identified as the boilers, heaters, and then the steam turbines and condensers respectively. Also, the effect of various parameters such as ambient temperature on the main components of the unit, as well as the effect of increasing steam inlet temperature, pressure, and mass flow rate on the exergetic efficiency of the unit were investigated [11]. M. E. Walker et al. investigated and estimated water consumption and steam production in the manufacturing industries of the United States. By extracting engineering estimates of the amount of freshwater consumed in industrial steam systems in the United States. Estimates were obtained using a thermodynamic steam system model based on steam system fuel usage and operating characteristics specific to industries. These estimates were divided the steam/water demand source in each sub-section including direct injection into processes, boiler blowdown, valve losses, and system leakage and failure [12]. H.Hu et al. designed a thermodynamic model of a 660MW thermal power plant with a hybrid cooling system (HCS) and assessed the changes in thermodynamic characteristics considering dry bubble temperature and relative humidity using the Epsilon calculation code. Performance characteristics of HCS were evaluated by comparing the dry cooling system (DCS) and the wet cooling system (WCS) [13]. W. Asvapoostikul et al. examined the performance of the HCS using tests and numerical simulations in a wide spectrum of working conditions. A computational model was developed to predict the behavior of DCS, WCS, and HCS [14]. G.Ahmadi et al. assessed a CHP system available in a petrochemical company regarding energy, exergy, and environmental (3E) aspects. The system encompassed steam generators, turbogenerators, and the steam distribution network for consumers. The results demonstrated that the highest rate of exergy destruction was in boilers, steam pressure-reducing stations, and turbogenerators, respectively [15]. G.R. Ahmadi et al. investigated Montazeri Steam Power Plant in Iran using energy and exergy analysis. These researchers assessed the performance of all the equipment in different conditions. They also provided a solution to promote the efficiency of the power plant [16]. B. Ali investigated water demand profiles in the future for the energy sector, identification of high-demand trajectories, and assessment of water demand for primary fuels and electricity generation in Alberta, Canada [17]. A. M. K. Vandani et al. evaluated exergy analysis and heat recovery energy of boiler blowdown of steam power plants. They selected a steam power plant in Iran and investigated the results of implementing a heat recovery system on the power plant in order to evaluate the impact of heat recovery on the system performance [18]. A. Gu, et al. assessed the association between the energy and water supply sectors in China quantitatively. The effect of energy conservation policy on water consumption in selected industrial sectors (e.g., ferrous and non-ferrous metals, petrochemical engineering, building materials, etc.) during the 11^{th} five-year plan was also determined [19]. O. J. Khaleel, et al dealt with reviewing the available literature on thermal power plants focusing on the overall structure of various cycles of the thermal power plant and its modeling, simulation, and improvement. The energy, exergy, and exergy destruction rate were assessed for each tool and suggestions were provided for improvement [20].

According to the importance of water conservation in the petrochemical industry as well as the urea and ammonia production in petrochemical units, a part of the steam cycle of Petrochemical Unit A has been modeled, analyzed, and assessed in this study. This choice is made due to the lack of comprehensive research regarding the steam cycle of the urea and ammonia production unit. The whole system is divided into 51 different points, and given the input data of each point (mass flow, temperature, and pressure), the intended parameters, such as power, thermal efficiency, exergy efficiency, exergy destruction rate, and mass balance, are calculated using the EES software. Scenarios and suggestions for saving steam and energy consumption have also been provided, and considering the rates of the intended utilities, the amount of savings for these scenarios has been calculated from an economic perspective as well. In some of the proposed scenarios, the Thermoflex module of the Thermoflow software has been employed. Strategies to reduce water consumption in some petrochemical equipment have been implemented and the amount of this saving in dollars per hour, per day, and per year have been obtained.

2. Problem Statement

In this study, a part of the steam cycle of the third phase of ammonia and urea production of Petrochemical Company A is modeled and analyzed, and the required parameters for cycle analysis are calculated using EES software. The equipment available in the modeling includes condensing and back pressure steam turbines; very high pressure, high pressure, and low-pressure steam headers; shell and tube condensers; boilers; feed water pumps; deaerators; steam drums; and pressure-reducing valves (Figure 1). The equations of energy, exergy, power, and mass balance in the above-mentioned equipment are solved and assessed using EES software.

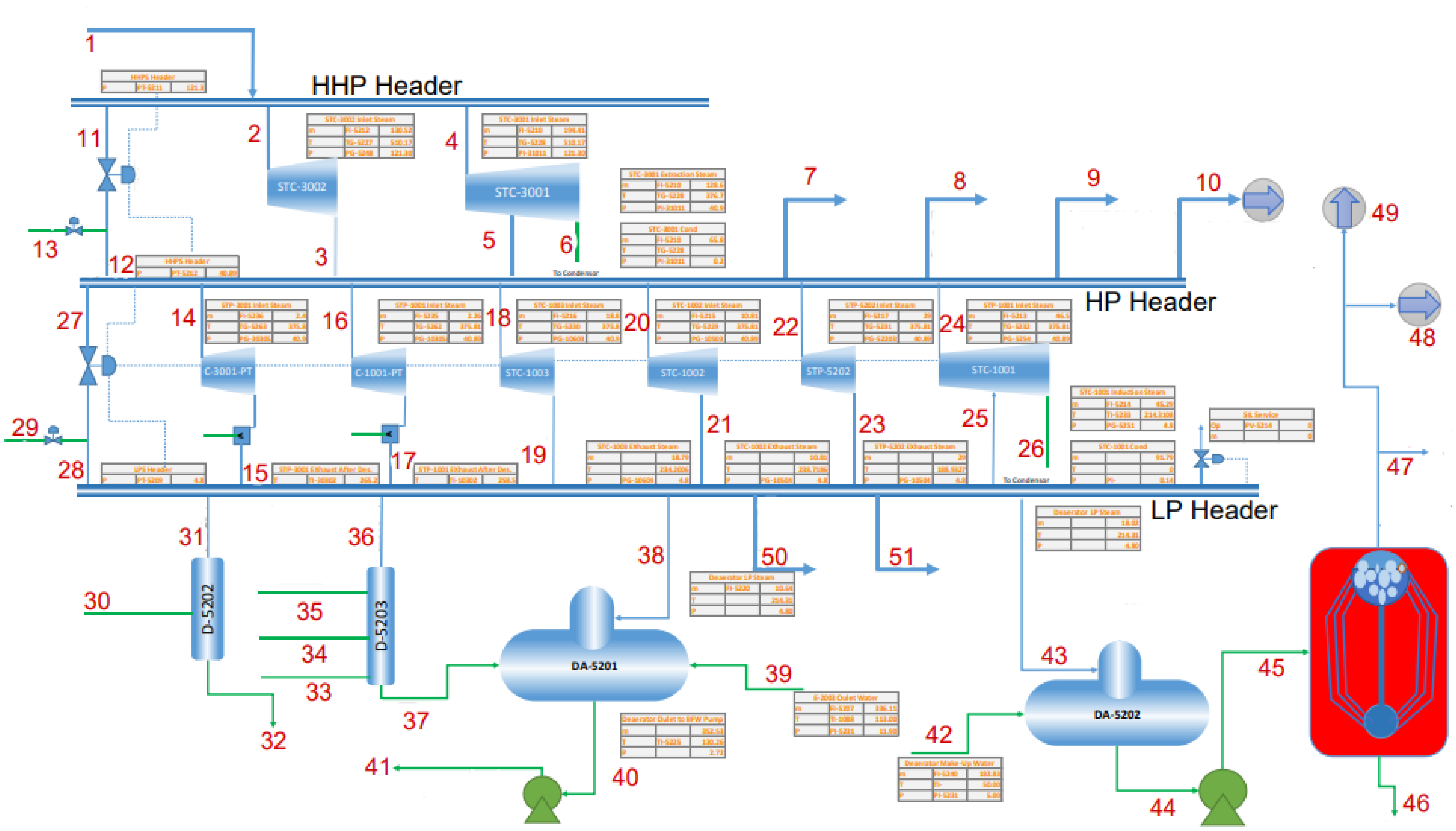


Figure 1: Petrochemical unit steam system

In the analyzed system, the input steam to the high high pressure (HHP) header (Point 1) is supplied from the SB-5201 boiler in the steam cycle. Also, the SB-5202 boiler available in the system is employed to supply the other phase steam in the petrochemical unit. The intended system is divided into 51 points, and based on the data of each point, such as temperature in ℃, pressure in terms of bar, and mass flow in terms of tons/hour, required parameters such as mass balance of headers, energy efficiency, exergy efficiency, power, and exergy destruction are calculated for various equipment. Table 1 provides the characteristics of each point of the flow.

Tabel 1. Characteristics of flows in the evaluated system [21]

Stream Number	Mass Flow Rate $\left(\frac{t}{h}\right)$	Temperature (℃)	Pressure (bar)
1	341.6845	510.17	121.3
2	130.52	510.17	121.3
3	130.52	375.1	40.89
4	194.41	510.17	121.3
5	128.6	376.7	40.89
6	65.8	53	0.2
7	154.3	375.8097	40.89
8	5.91	375.8097	40.89
9	2.7	375.8097	40.89
10	0.667088	375.8097	40.89
11	16.4565	510.17	121.3
12	16.4565	375.1	40.89
13	0	0	0
14	2.4	375.8	40.89
15	2.4	265.2	4.8
16	2.26	375.8	40.89
17	2.26	258.5	4.8
18	18.8	375.8	40.89
19	18.8	234.2006	4.8
20	10.81	375.8	40.89
21	10.81	238.7186	4.8
22	29	375.8	40.89

Stream Number	Mass Flow Rate $\left(\frac{t}{h}\right)$	Temperature (°C)	Pressure (bar)
23	29	188.9327	4.8
24	46.5	375.8	40.89
25	45.29	214.3108	408
26	91.97	53	0.14
27	2.229462	375.8	40.89
28	2.229462	265	4.8
29	6.904928	250	4.8
30	3.6	326.8293	4.8
31	1.49	150.30	4.8
32	2.11	150.30	4.8
33	2.7	254	4.8
34	1.157	328	4.8
35	5.673	328	4.8
36	3.40563	150.3045	4.8
37	6.12	150.30	4.8
38	10.64	214.31	4.8
39	336.11	113	11.9
40	352.53	130.26	2.72
41	341.3865	130	121.3
42	182.83	50	4.8
43	18.02	214.31	4.8
44	317.1	107	2.29
45	158.55	107	58
46	0.99885	257.4394	45
47	5.87	390	45
48	18	390	45
49	175.9	390	45
50	2.35	214.3108	4.8
51	1	214.3108	4.8

Before present the equations and the other section of study, some limitations of this study are listed as below:

1) Low prices of energy carriers and water; In countries where water and energy are heavily subsidized and cheap, there is little economic incentive to invest in saving projects.

2) Ensuring product quality and process stability; Any change in operating parameters (such as temperature, pressure, and steam flow rate) to reduce water consumption can affect the final product quality and process stability. The main priority of petrochemical companies has always been product production and less attention has been paid to the aspect of saving water and energy consumption.

3) The need to stop the unit for optimization; To implement these scenarios for reducing water and energy consumption, some of the equipment of the industrial unit may need to be temporarily taken out of operation. Therefore, the company will incur financial losses. These scenarios can be applied during periodic maintenance operations that are carried out every few years.

3. Governing Equations

A series of equations and relations have been used to modeling the analyzed system, which are expressed as follows.

In this section, the exergy relations are calculated with respect to the ambient pressure and temperature. In solving the exergy equations, the conservation laws of mass and energy are also taken into account. The efficiency relations for the turbine and pump are considered to be isentropic (constant entropy). It is assumed that the fluid flow through the pump and turbine is steady over time (steady-state flow). The fluid in pump and turbine are incompressible and compressible respectively. In addition, friction between the fluid and the components of the pump and turbine is neglected.

The physical exergy of flows is obtained from the following equation [22], [23]:

$$\Psi = \dot{m} \times [(h_i - h_0) - T_0 \times (s_i - s_0)] \tag{1}$$

Exergy destruction rate is in the form of the following relationship:

$$I = |Ex_{in} - Ex_{out}| \tag{2}$$

Ex_{in} and Ex_{out} are input exergy and output exergy, respectively. The turbine isentropic efficiency and turbine power are calculated as equations (3) and (4):

$$\eta_{th,Turbine} = \frac{w_a}{w_s} = \frac{h_1 - h_{2a}}{h_1 - h_{2s}} \quad (3)$$

$$\dot{W} = \dot{m} \times (h_1 - h_{2a}) \quad (4)$$

he isentropic efficiency and power of the pumps are calculated in the form of relations (5) and (6):

$$\eta_{th,Pump} = \frac{W_s}{W_a} = \frac{v(p_2 - p_1)}{h_{2a} - h_1} = \frac{h_{2s} - h_1}{h_{2a} - h_1} \quad (5)$$

$$\dot{W}_{pump} = \dot{m} \times (h_2 - h_1) \quad (6)$$

The exergy efficiency of pumps and turbines is as follows:

$$\eta_{exergy} = \frac{Ex_{out}}{Ex_{in}} \quad (7)$$

In condensers, exergy efficiency and exergy destruction rate are calculated in the form of relations (8) and (9):

$$\eta_{exergy} = \frac{\dot{m}_c(\Psi_e - \Psi_i)_c}{\dot{m}_h(\Psi_i - \Psi_e)_h} \quad (8)$$

$$I = Ex_{cold,in} - Ex_{cold,out} \quad (9)$$

In the above relations, subscript c means cold flow and subscript h means hot flow. In deaerators and steam drums, exergy efficiency and exergy destruction rate are obtained by relations (10) and (11):

$$\eta_{exergy} = \frac{\sum Ex_{outlet}}{\sum Ex_{inlet}} \quad (10)$$

$$I = \left|\sum Ex_{inlet} - \sum Ex_{outlet}\right| \quad (11)$$

In boilers, exergy efficiency and exergy destruction rate are calculated by relations (12) and (13)

$$\eta_{exergy} = \frac{Ex_{in} - Ex_{out}}{Ex_{fuel}} \quad (12)$$

$$I = Ex_{fuel} + Ex_{in} - Ex_{out} \quad (13)$$

Ex_{fuel}, is chemical exergy of the fuel. The fuel used in this cycle is natural gas (CH_4). Also, the chemical exergy of the fuel is calculated as follows:

$$Ex_{chemical,fuel} = \gamma_f \times \dot{m}_f \times LHV \quad (14)$$

$$Ex_{fuel,total} = Ex_{fuel,boiler1} + Ex_{fuel,boiler2} \quad (15)$$

The low heating value (LHV) of the fuel for natural gas is 47.3 megajoules and the exergy factor (γ_f) for it is 1.03 [5]. Also, $\dot{m}_f$ expresses the fuel mass flow rate. The fuel flow rate of the main boiler (SB-5201) whose produced steam enters the HHP steam header at point 1 of the cycle is equal to 55 tons/hour and the fuel flow rate of the side boiler of the cycle is equal to 14.7 tons/hour.

$$\eta_{exergy,cycle} = \frac{\dot{W}_{net,cycle}}{Ex_{fuel,boiler1} + Ex_{fuel,boiler2}} \times 100 \quad (16)$$

$$\dot{W}_{net,cycle} = \sum \dot{W}_T - \sum \dot{W}_P \quad (17)$$

Using the results obtained from equations (16) and (17), the exergy efficiency of the whole system is 45.64% and the net power of the system is 48866 kw.

<u>Mass balance relationships of headers</u>

$$\dot{m}_1 = \dot{m}_2 + \dot{m}_3 + \dot{m}_{Letdown,header\ HHP} \quad (18)$$

$$\dot{m}_3 + \dot{m}_5 + \dot{m}_{Letdown,headerHHP} = \dot{m}_7 + \dot{m}_8 + \dot{m}_9 + \dot{m}_{10} + \dot{m}_{14} + \dot{m}_{16} + \dot{m}_{18} + \dot{m}_{20} + \dot{m}_{22} + \dot{m}_{24} + \dot{m}_{Letdown,headerHP} \quad (19)$$

$$\dot{m}_{15} + \dot{m}_{17} + \dot{m}_{19} + \dot{m}_{21} + \dot{m}_{23} + \dot{m}_{29} + \dot{m}_{31} + \dot{m}_{36} + \dot{m}_{Letdown,headerHP} = \dot{m}_{26} + \dot{m}_{38} + \dot{m}_{43} + \dot{m}_{50} + \dot{m}_{51} \quad (20)$$

4. Results

4-1) Validation

In order to verify the present research results, the parameters of two items of system equipment in the design state based on the information available in the steam cycle documents of Petrochemical Unit A and the obtained results are compared and shown in Table 2.

Table 2: Verification of simulation results with the values of design documents of two items of equipment

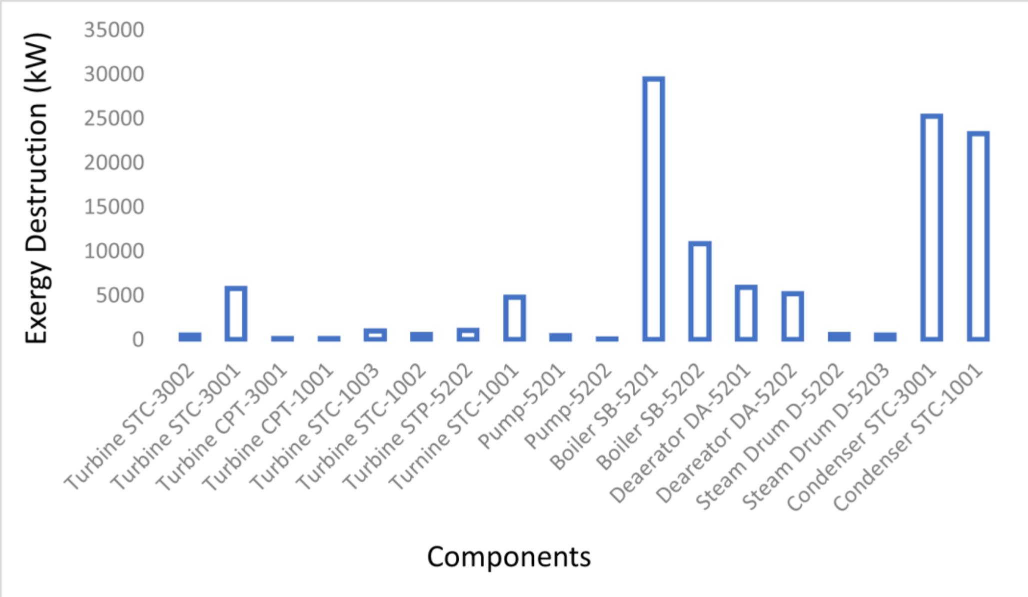
Parameter	Design Mode Value	Simulation Mode	Percentage Error
Pump STP-5202	2311 (kW)	2460 (kW)	6.24%
Turbine STC-3002	8395 (kW)	8614 (kW)	2.5%

4-2) Cycle Energy, Exergy, and Power Analysis Results

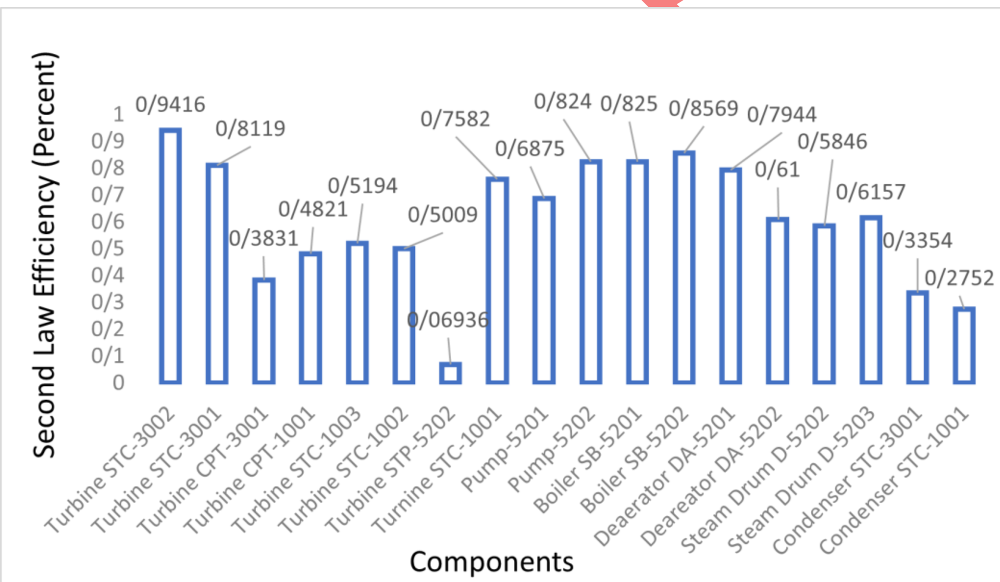
After solving the group of equations 1 to 13, the parameters of exergy efficiency, energy efficiency and exergy destruction rate are calculated for the equipment listed in Table 3 using EES software.

Table 3. Exergy efficiency and exergy destruction rate of the equipment in the system

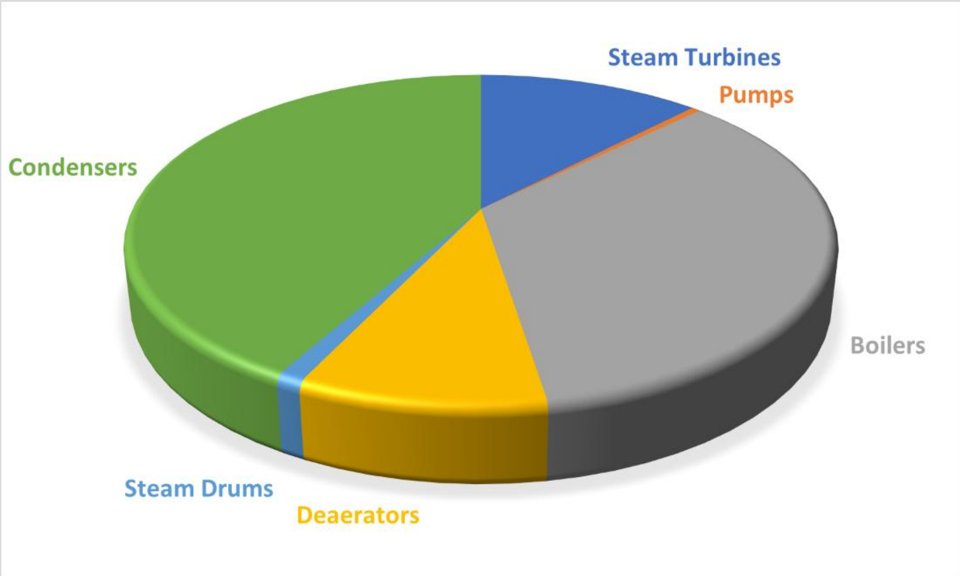
Equipment Name	Energy Efficiency	Exergy Efficiency	Exergy Destruction (kW)
Turbine STC-3002	0.73	0.9416	534.7
Turbine STC-3001	0.7167	0.8119	5800
Turbine CPT-3001	0.3385	0.3831	154.3
Turbine CPT-1001	0.3676	0.4821	138
Turbine STC-1003	0.4732	0.5194	1013
Turbine STC-1002	0.4535	0.5009	598.8
Turbine STP-5202	0.6738	0.6936	1087
Turbine STC-1001	0.6365	0.7582	4798
Pump 5201	0.71	0.6875	501.3
Pump 5202	0.5049	0.824	57.31
Boiler SB-5201		0.825	29509.376
Boiler SB-5202		0.8569	10889.22
Deaerator DA-5201		0.7944	5952
Deaerator DA-5202		0.61	5212
Steam Drum D-5202		0.5846	629.2
Steam Drum D-5203		0.6157	551.7
Condenser STC-3001		0.3354	25286
Condenser STC-1001		0.2752	23313


Exergy Destruction (kW)
35000
30000
25000
20000
15000
10000
5000
0
Turbine STC-3002
Turbine STC-3001
Turbine CPT-3001
Turbine CPT-1001
Turbine STC-1003
Turbine STC-1002
Turbine STP-5202
Turnine STC-1001
Pump-5201
Pump-5202
Boiler SB-5201
Boiler SB-5202
Deaerator DA-5201
Deaerator DA-5202
Steam Drum D-5202
Steam Drum D-5203
Condenser STC-3001
Condenser STC-1001
Components

(a)


Second Law Efficiency (Percent)
1
0/9
0/8
0/7
0/6
0/5
0/4
0/3
0/2
0/1
0
0/9416
0/8119
0/3831
0/4821
0/5194
0/5009
0/06936
0/7582
0/6875
0/824
0/825
0/8569
0/7944
0/61
0/5846
0/6157
0/3354
0/2752
Turbine STC-3002
Turbine STC-3001
Turbine CPT-3001
Turbine CPT-1001
Turbine STC-1003
Turbine STC-1002
Turbine STP-5202
Turnine STC-1001
Pump-5201
Pump-5202
Boiler SB-5201
Boiler SB-5202
Deaerator DA-5201
Deaerator DA-5202
Steam Drum D-5202
Steam Drum D-5203
Condenser STC-3001
Condenser STC-1001
Components

(b)



(c)

Figure 2. (a) Contribution of exergy analysis of different components of the steam cycle, (b) Second law efficiency, (c) Exergy destruction per plant's components

As seen in Figure 2, exergy efficiency and exergy destruction rate have been calculated for the equipment available in the steam system. The highest exergy destruction rate is related to the cycle main boiler (SB-5201), which supplies steam entering the HHP header, and the lowest is related to pump 5202. The combustion process in the boiler generates a significant amount of irreversibility and increases the entropy of the system, a large amount of exergy destruction occurs in the boiler. Exergy destruction or irreversibility is an amount of loss occurring in the process. The results from part (b) of the graph show that the highest second-law efficiency belongs to the main steam turbine of the cycle. In this steam turbine, the high inlet temperature and pressure enable energy conversion with higher efficiency. Overall, the highest exergy destruction rates are related to boilers and condensers.

4-3) The effect of header pressure and temperature on exergy efficiency and net cycle power

According to the obtained values and the graphs in Figures 3, 4 and 5, the effect of header temperature and pressure on the exergy efficiency and net power of the cycle has been investigated.

As the temperature of header 1 increases, the exergy efficiency decreases and the net power 1 increases, the exergy efficiency decreases and the net power of the cycle increases. By increasing the pressure of header 1, both the exergy efficiency and the net power of the cycle have increased. As the temperature of header 2 increases, the exergy efficiency and net power of the cycle increase. As the pressure of header 2 increases, the exergy efficiency and also the net power of the cycle decrease. As the temperature of header 3 increases, both the exergy efficiency and the net power of the cycle increase. By increasing the pressure of header 3, the exergy efficiency increased and the net power of the cycle decreased.

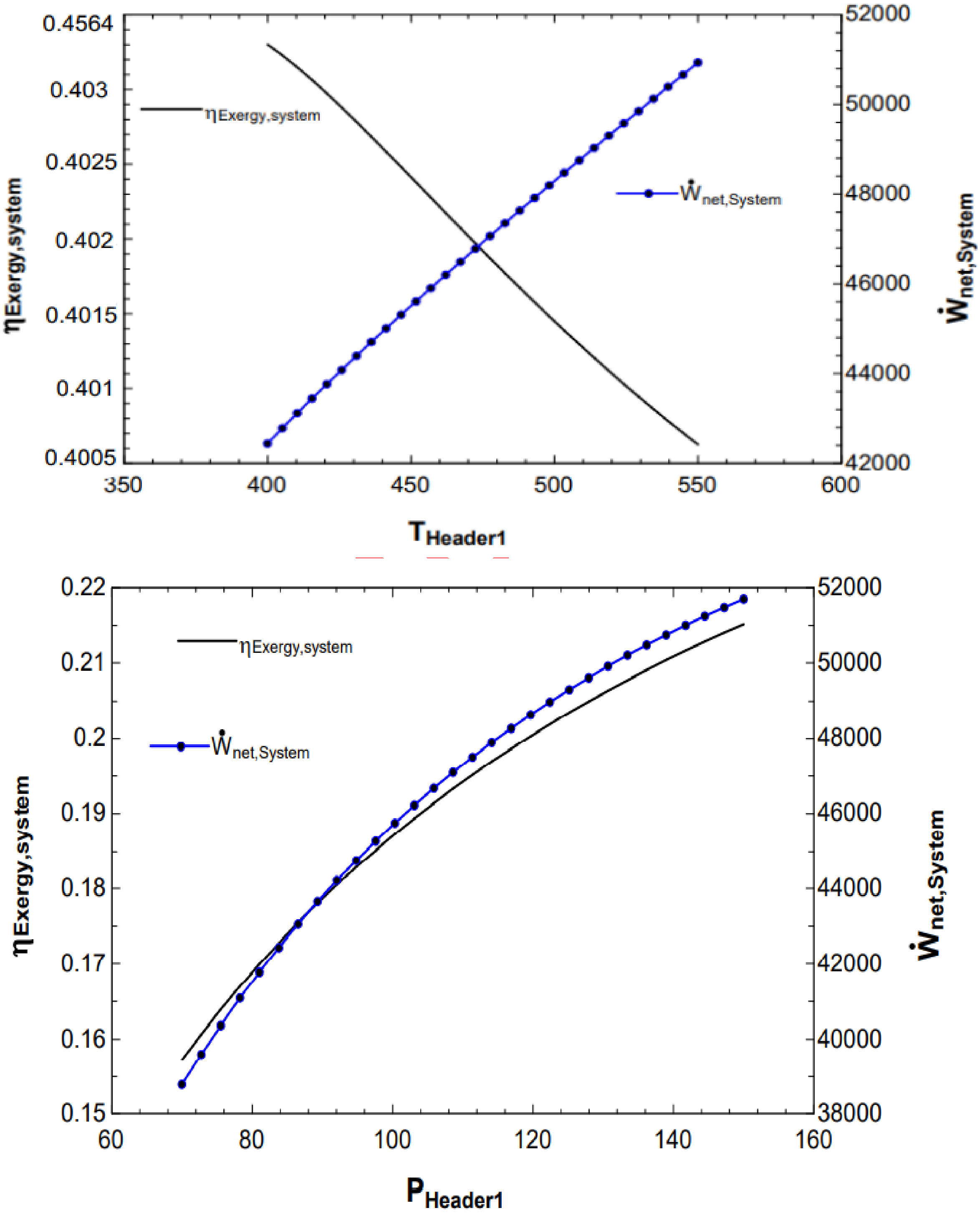


Figure (3). Changes in exergy efficiency and net cycle power as a function of temperature and pressure of header 1

According to Figure 3, with the increase of the temperature at header 1, the system's exergy efficiency decreases and the net work increases. On the other hand, with the increase of the pressure at header 1, both the system's exergy efficiency and net work increase.

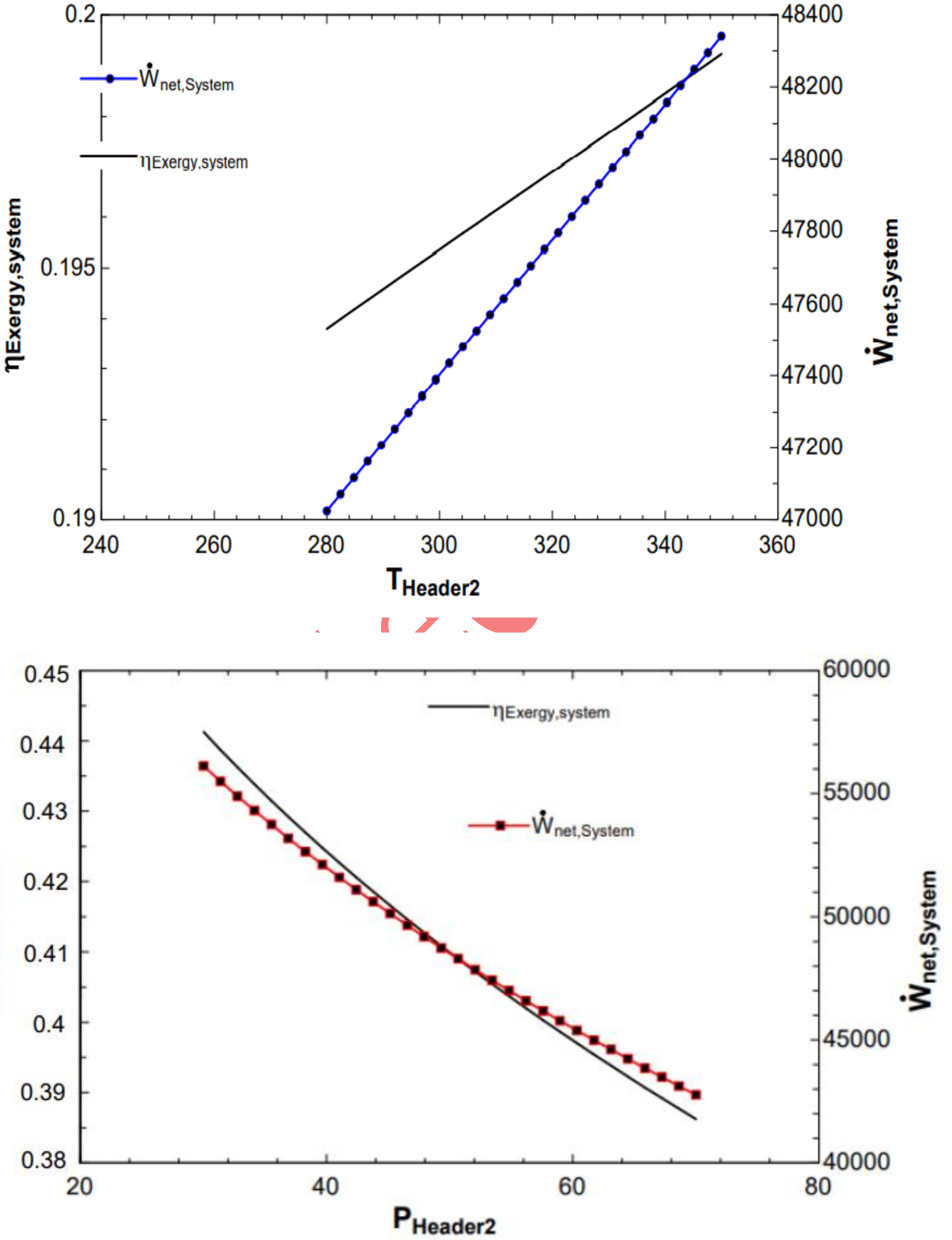


Figure (4). Changes in exergy efficiency and net cycle power as a function of temperature and pressure of header 2

According to Figure 4, with the increase of the temperature at header 2, the system's exergy efficiency and net work increase. Also, with the increase of the pressure at header 2, the system's exergy efficiency and net work decrease.

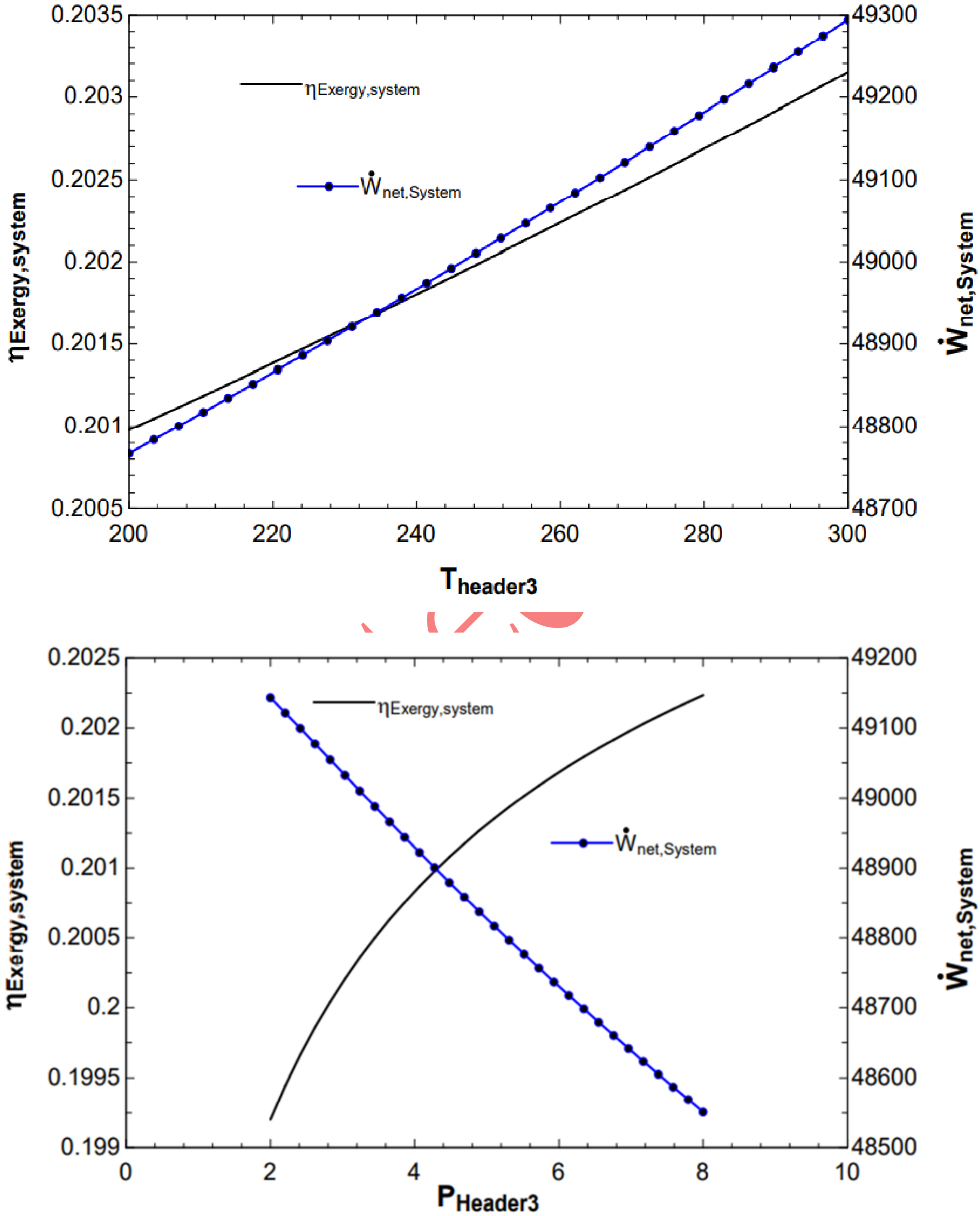


Figure (5). Changes in exergy efficiency and net cycle power as a function of temperature and pressure of header 3

According to the results in Figure 5, with the increase of the temperature at header 3, both the system's exergy efficiency and net work increase. On the other hand, with the increase of the pressure at header 3, the system's exergy efficiency increases while the net work decreases.

4-4) Solutions to Reduce Water and Energy Consumption in the Intended System

In this section, solutions and scenarios have been raised for reducing water and energy consumption in Petrochemical Unit A, which are described in the following.

4-4-1) Improving the Steam Consumption of the STC-3001 Condensing Turbine

STC-3001 steam turbine is a condensing turbine with controllable extraction. Since the extraction of steam turbines extracted in petrochemical units usually enter the lower level header, such turbines use controllable extractions. According to the turbine design-related documents, it is observed that this turbine used its maximum capacity in the low pressure (LP) section, while the high pressure (HP) section has a long distance from the maximum condition. From the exergy perspective, if the flow has higher temperature and pressure, it will have more production power and higher efficiency, meaning that more HHP header steam usage and reduced HP header steam consumption will generally promote efficiency. In this section, the Thermoflex module of the Thermoflow software has been employed to observe the intended changes. The operational data of the STC-3001 steam turbine are shown in Figure 6.

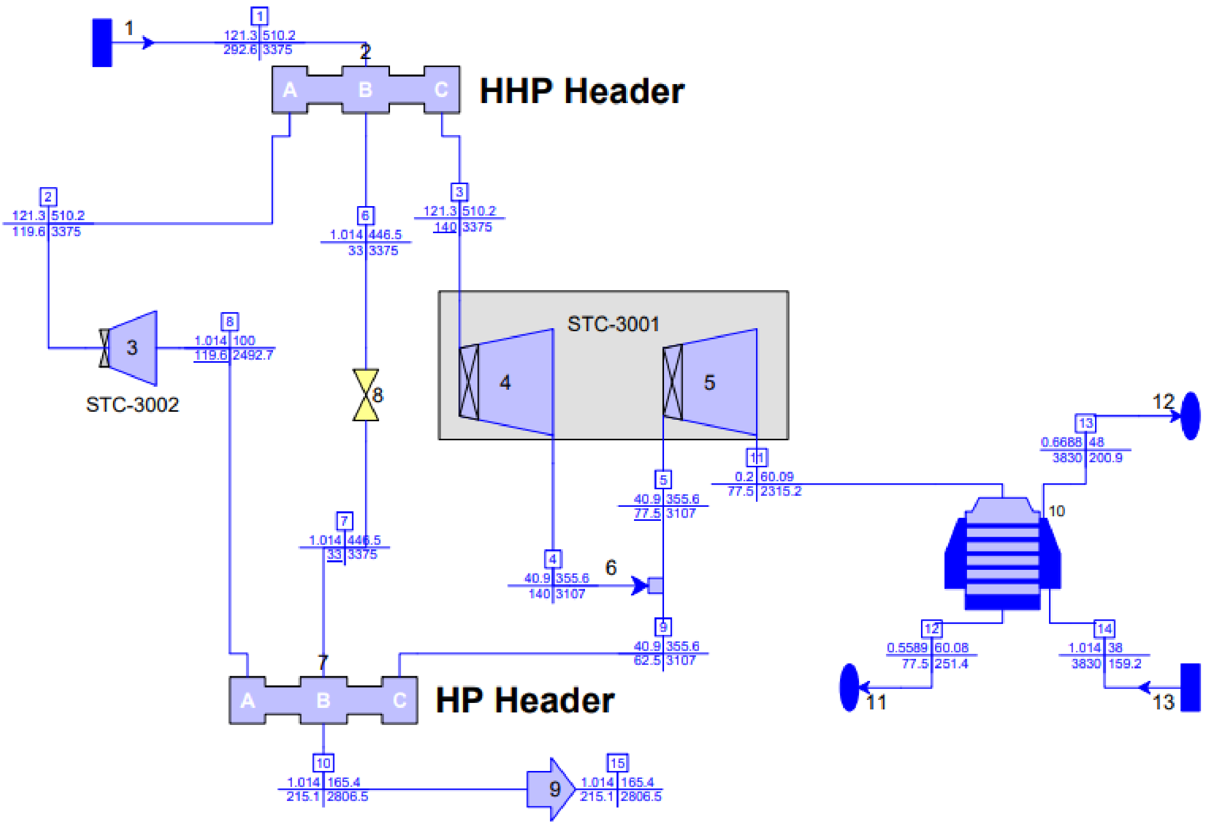


Figure 6. STC-3001 steam turbine performance data

As seen in Figure 6, the mass flow of steam entering the HHP header is 292.6 tons/hour. Moreover, the mass flow of steam entering the STC-3001 turbine HP section at Point 3 is 140 tons/hour and the steam entering the STC-3001 turbine LP section at Point 5 is 77.5 tons/hour. Considering the mentioned topics, the amount of steam entering the STC-3001 turbine HP section is supplied via the excess steam that goes from the valve to the HP header and has reached 162.31 tons/hour with the same temperature and pressure conditions, and the steam entering the turbine LP section and the condenser has decreased by 64.8 tons/ hour. Additionally, the amount of steam let-down from the HHP header to the HP header from the valve between the two headers has reached zero. The results of applying these changes are shown in Figure 7.

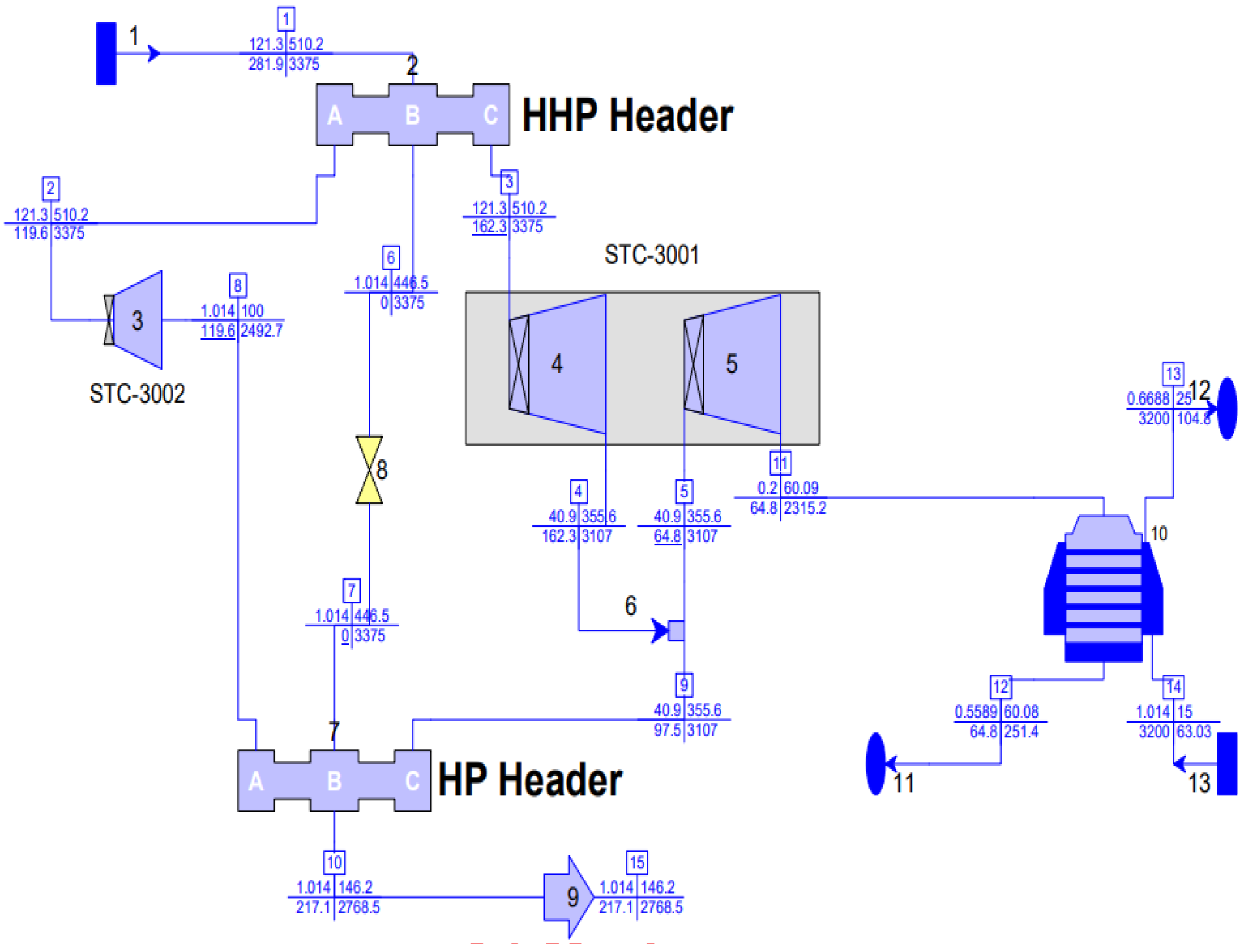


Figure7. Simulation results after applying changes in STC-3001 steam turbine

As seen, after applying the intended changes, the amount of steam entering the HHP header at Point 1 has decreased by 10.7 tons/hour. Furthermore, based on the system design-related documents, in the operating conditions of the complex, an amount of 2.11 $\frac{m^3}{h}$ of sprayed demin water (deionized water) has been used for desuperheating the steam exiting the let-down between the two HHP and HP steam headers. By applying the intended changes, besides decreasing the amount of steam entering the HHP header by 10.7 tons/hour, the amount of 2.11 $\frac{m^3}{h}$ of demin water required for desuperheating the steam exiting the valve between the two headers also decreases. The rate of utilities considered for economic calculations has been calculated in Table 4, and the amount of savings after applying the intended changes has been calculated in Table 5.

Table 4. Utility rates considered for economic calculations [21]

Utility Type	Rate
Steam	$15\ \frac{\$}{ton}$
Electricity	$0.055\ \frac{\$}{kWh}$
Demin Water	$1.5\ \frac{\$}{m^3}$
Cooling Water	$0.1\ \frac{\$}{ton}$

Table 5. The amount of savings achieved after applying the desired changes

Steam reduction rate	$10.7\ \frac{ton}{hr}$
The amount of demin water has decreased	$2.11\ \frac{m^3}{hr}$
Savings per hour (in dollars)	163.66 $
Daily savings (in dollars)	3,927.96 $
Annual savings (in dollars)	1,433,705 $

4-4-2) Reducing the Temperature of the Cooling Water Returning from STC-3001 Condenser

According to applying the intended changes to the operational data of the STC-3001 steam turbine, in addition to reducing the steam entering the HHP header and demin water for desuperheating the let-down steam from the valve between the two headers, the amount of water temperature returning from the STC 3001 shell and tube condenser has also decreased. Also amount of steam has decreased by 4.08%. Figures 8 and 9 display the conditions of the condenser before and after the changes, respectively. In Figures (8) and (9), pressure (P) is in bar, temperature (T) is in degrees Celsius, enthalpy (H) is in kJ and flow rate (M) is in tons per hour. Also, 'sub' refers to the temperature of the subcooled liquid in degrees Celsius.

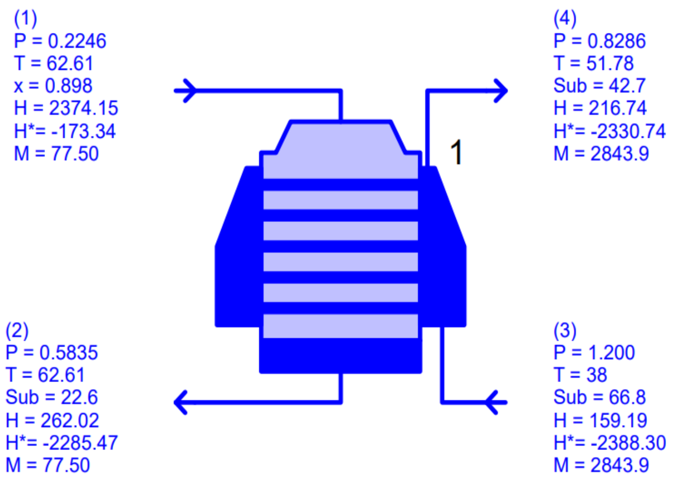


Figure 8. STC-3001 condenser performance data

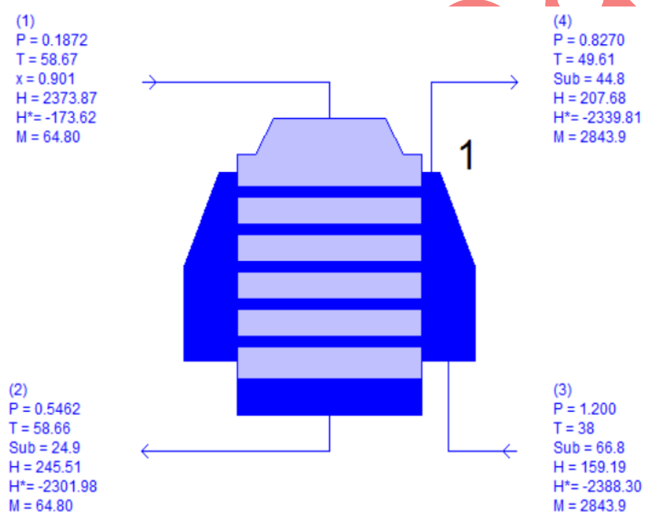


Figure 9. The results of the STC-3001 condenser data after applying the desired changes to STC-3001 turbine

As seen, after applying the intended changes to the STC-3001 steam turbine, the water temperature returning from the condenser has decreased by 2.17 °C.

4-4-3) Improving the Pressure Condition of the STC-1001 Steam Turbine Condenser

One of the significant cases in utilizing steam turbines is the proper adjustment of the turbine steam sealing. In condensing turbines, the main duty of steam sealing is to prevent the leakage of ambient air into the mainstream, leading to increasing non-condensable gases in the condenser and then increasing the condenser pressure [24].

The data of the STC-1001 turbine in the design and operational mode are shown in Table 6.

Tabel 6. STC-1001 steam turbine design and operational mode data [21]

Features	Mass Flow Rate (ton/hr)		Pressure (bar)		Temperature (°C)	
Inlet to turbine from HHP header	**40.45**	46.5	**42.4**	40.9	**375**	375.81
Inlet to turbine from LP header	**52.95**	45.29	**4.4**	4.8	**218**	214.3108
Output from the turbine and input to the condenser	**93.4**	91.79	**0.16**	0.271	**53**	53

In Table (6), the numbers are written in bold and underline format represent the design condition data, and the numbers are written in black represent the operating condition data of the STC-1001 steam turbine.

Comparing the data of the STC-1001 turbine design and operating states has indicated that the main reason for the deviation from the design state conditions is the condenser's increased pressure. When the amount of steam sealing is less than the required amount, it will not be able to seal the Gland; therefore, the air enters the condenser through the packings, non-condensable gases increase, and subsequently, the condenser pressure heightens and the turbine efficiency decreases. The condenser pressure indeed increases from 0.16 to 0.271 bar, leading to increased steam consumption of the HP header by 6 tons/hour. By modifying the Gland steam system, the turbine utilization is facilitated and the condenser pressure is reduced. Also amount of steam has decreased by 13%. The amount of savings stemming from implementing this solution is shown in Table 7.

Tabel 7: Savings from STC-1001 Steam Turbine Gland System Improvements

The amount of steam consumption reduction of the HP header	$6\,\frac{t}{h}$
Savings per hour (in dollars)	$90\,\frac{\$}{h}$
Daily savings (in dollars)	2160 $
Annual savings (in dollars)	788,400 $

5) Conclusion

In this article, the water-energy nexus is investigated in the third phase of urea and ammonia of Petrochemical Company A. The intended system is divided into 51 points, and given the data of each point, such as temperature, pressure, and mass flow, the equations of energy, exergy, power, and mass balance, are calculated using the EES software and Thermoflex module of the Thermoflow softwares. The results and solutions for saving steam and energy consumption are as the following items:

- ❖ Considering the STC-3001 steam turbine design-related documents, it is observed that this turbine used its maximum capacity in the LP section, while the HP section has a long distance from the maximum condition. After applying the intended changes, the amount of steam entering the HHP header at Point 1 is 10.7 tons/hour and the amount of demin water necessary for desuperheating the steam exiting the valve between the two headers decreased by 2.11 m^3/h, which is equivalent to an annual savings of $1,433,705.
- ❖ Considering applying the intended changes to the operational data of the STC-3001 steam turbine, the water temperature returning the STC 3001 shell and tube condenser has also decreased by 2.17 °C.
- ❖ Comparing the data of the STC-1001 turbine design and operating states has indicated that the main reason for the deviation from the design state conditions is the condenser's increased pressure. In fact, by increasing the condenser pressure from 0.16 to 0.271 bar, the air enters the condenser through the packings, leading to increasing non-condensable gases and subsequently decreasing the turbine efficiency. Thus, by proper adjustment of the steam sealing, culminating in saving approximately 6 tons/hour of steam consumption, which is equivalent to an annual savings of $778,400.

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