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EXERGY BASED OPTIMIZATION OF A BIOMASS AND SOLAR FUELLED CCHP HYBRID SEAWATER DESALINATION PLANT

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ABSTRACT

Integrated energy systems utilizing renewable sources are a sustainable and environmentally substitution for conventional fossil fired energy systems. A CCHP hybrid seawater desalination plant with two inputs such as biomass and solar energy and four useful outputs such as cooling, heating, power and distillated water is presented and investigated in this paper. The proposed system includes evacuated tube solar collectors, biomass burner, organic rankine cycle (ORC), absorption chiller, heater and multi effect desalination system (MED). The results showed that the proposed system is able to produce 802.5KW as power, 10391 KW as heating, 5658 KW as cooling and 9.328 kg/s distillated water. Energy efficiency of the system is 61 %, the exergy efficiency is 7 % and the main sources of exergy destructions are biomass burner, evacuated tube solar collectors and vapor generator. Exergy optimization is carried out in order to find the optimum point of system.

INTRODUCTION

Increasing world population and demand for energy and potable water lead to burn more fossil fuels and its result is release a large amounts of greenhouse gases, particularly carbon dioxide. In order to reduce CO_2 emission using renewable energy instead of fossil fuels is a main challenge for sustainable development.

CCHP systems are a kind of cogeneration systems with three outputs and CCHP hybrid seawater desalination plant can be considered as a multigeneation system since they have more than three outputs (power, heating, cooling and fresh water).

Issues like fossil fuel depletion and climate change amplify the advantages and significance of efficient multigeneration energy systems [1]. Dincer and Zamfirescu[2]showed that multigeneration systems based on renewable energies as clean and free alternatives of fossil fuels reduce fuel prices and emissions, compared to conventional systems such as cogeneration or trigeneration systems. Other studies show that exergy efficiency ofmultigeneration systems using an ORC with renewable energy source increase up to 10% and integration of two renewable energy sources such as biomass and solar energy can be beneficial with higher energy and exergy efficiency than a single renewable energy source [3,4,5]. Dincer and Zamfirescu [6] performed multigeneration renewable energy based system has better efficiency, sustainability and environment. Rubio-Mayaet et al. [7] designed a multigeneration system fuelled by natural gas, solar and gasified biomass and conclude that renewable energy is the source of the reduction of CO_2 and environmental impact. Minciuc et al. [8] offered an approach for investigating of the multigeneration system and reported optimal energetic efficiency of the system. Ahmadi et al. [9] presented an exergy-based optimization of a multigeneration energy system to produce power, heating, cooling and domestic hot water. They find the best design parameters of the system considering exergy efficiency. Zamfirescu et al. [10] have examined the multigeneration system as a method of improving the exergy efficiency of the nuclear power system. Ratlamwala et al. [11] analyzed the performance of a novel integrated geothermal-based system for multigeneration, for producing cooling, heating, power generation, hot water and hydrogen. Ozlu and Dincer [12] developed a solar-wind hybrid multigeneration system and analyzed the energy and exergy efficiency of the system which were higher than equivalent single energy systems efficiencies. Sharifishourabi et al.[13] showed that a hybrid combination of renewable energy sources such as solar and wind energy can be a suitable alternative for power generation. Dube Kerme and Orfi [14] presented thermodynamic modeling of organic Rankine cycle (ORC) driven by parabolic trough solar collectors. Solar energy can be collected in many methods such as evacuated tube solar collectors (ETC) which is used in this study. Biomass is mainly derived from living or dead matter present on earth. Bagasse is a kind of biomass that is selected as one of the energy sources for the studied system and biomass fuels can be obtained from agricultural production wastes especially having

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been related to sugarcane such as Bagasse. J. Werther et al.[15] studied the processes of different agricultural wastes combustion including sugarcane. L.A.B Cortez et al. [16] did Exergy analysis in order its heat to be used in bagasse combustion. A. Bhattacharja et al. [17] studied and researched on power generation process through the utilization of bagasse gas integrating system in terms of energy and exergy, but a CCHP hybrid desalination plant driven by solar energy and bagasse combustion has not been analyzed from the viewpoint of thermodynamics.

In this paper, energy and exergy analysis of a CCHP hybrid seawater desalination plant driven by bagasse combustion and solar energy is investigated. Optimum point of system is carried out considering the exergy efficiency as an objective function.

SYSTEM DESCRIPTION

Figure 1 shows the schematic of suggested CCHP hybrid desalination system which can be divided into Evacuated Tube Collector (ETC), biomass burner, Organic Rankine Cycle (ORC), absorption chiller, heater and Multi Effect Desalination system (MED). Outputs of the proposed system are electricity, heating, cooling and fresh water.

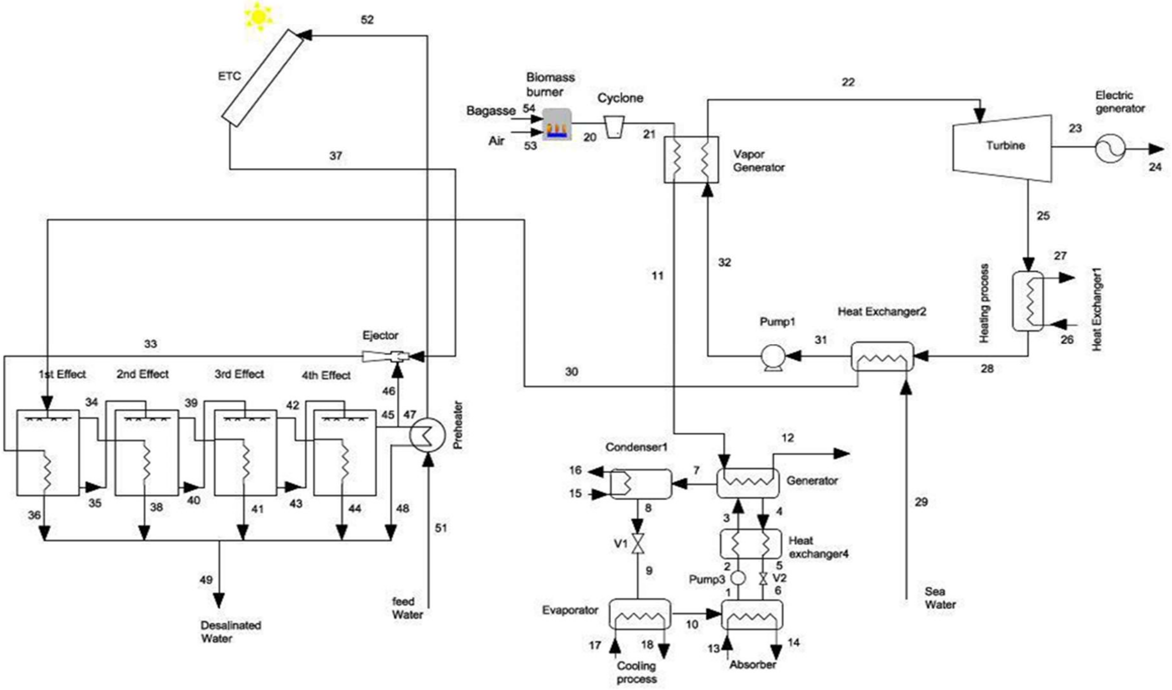

Figure 1. Schematic of CCHP hybrid desalination system

The suggested system is based on two renewable energy sources, solar energy which the solar radiation is collected through ETC, bagasse which is combusted in a biomass burner. Hot combustion gases pass through the vapor generator and enter to a single-effect absorption cycle which uses LiBr-H_2O to provide cooling. In the ORC the heat released from biomass burner is transferred to R123 and causes to make a superheated vapor for producing power in ORC turbine. The wasted energy of turbine is used by a heater to provide heating. In Heat Exchanger2 the remaining heat is transferred to sea water to preheat it and R123 enters to Vapor Generator to complete the cycle. Last purpose of this system is producing fresh water by a MED which contains four effects. Because the sufficient and low cost heating can be provided in this system, MED is best option compare to any other types of desalination plant. Seawater enters to first effect after preheating and a part of it is converted to fresh water. In each effect pure water is produced at lower pressure and lower temperature than the previous effect. The produced vapor of each effect feeds as the heating steam for the next effect and so on. Feed water passes through preheater and enters to ETC then steam which is produced in ETC enters to ejector. Ejector by increasing inlet steam pressure provides an appropriate pressure for the first effect of MED entrance. Data have been utilized in Khuzestan province, Iran. This province is among the most prone areas in Iran in exploitation of solar energy having had over 300 sunny days [18] and there are 86588 hectares under cultivation of which about 6536976 tons has been attained from 9 large sugar production factories [19].

THERMODYNAMIC ANALYSIS

Thermodynamic analysis including energy and exergy is carried out using following assumptions:

- The reference-environment state has a temperature $T_0 = 298$ K and a pressure $P_0 = 100$ KPa.
- The changes in kinetic and potential energy and exergy terms are negligible.
- HHV for bagasse is 16793 KJ/Kg
- The higher heating value (HHV) is the primary contributor to the chemical exergy of a biomass fuel and obtained from bellow equation[20]:

$$\frac{e_f^{-ch}}{HHV} \approx 1.00 - 1.04$$

First and *second thermodynamic laws have been to each component as below [21]:*

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

$$\sum \dot{Q} - \sum \dot{W} = \sum \dot{m}_{out} h_{out} - \sum \dot{m}_{in} h_{in} \tag{2}$$

$$\dot{E}x_Q + \sum_i \dot{m}_i ex_i = \sum_e \dot{m}_e ex_e + \dot{E}x_W + \dot{E}x_D \tag{3}$$

The exergy of a substance is often divided into four components. Two common ones are physical and chemical exergy. The two others, kinetic and potential exergy, are assumed to be negligible here:

$$\dot{E}x_{ph} = (h - h_0) - T_0(S - S_0) \tag{4}$$

$$\dot{E}x_{ch} = \sum ex_k \dot{E}x_{ch}^k + RT_0 \sum x_k \ln x_k \tag{5}$$

Bagasse combustion equation based on wet is as following [17]:

$$[0.268\,C + 0.239\,H_2 + 0.099\,O_2 + 0.394\,H_2O + Ash] + [1.075\,N_2 + 0.289\,O_2 + 0.013Ar] \rightarrow [0.268\,CO_2 + 0.633\,H_2O + 1.075\,N_2 + 0.013\,Ar] \tag{6}$$

RESULTS AND DISCUSSION

Thermodynamic modeling is implemented through Engineering Equation Software (EES) [22] using input data which is shown in Table 1, and the result of thermodynamic modeling is presented in Table 2. The system is proposed for locating in Ahwaz, Iran since it has sufficient sources of bagasse and solar radiation. Average daily solar radiation is extracted from NASA internet site [23].

Table 1. Input data for thermodynamic modeling

Parameters	**Values**
Turbine inlet temperature	130 ^{0}C
Turbine inlet pressure	700 KPa
Turbine pressure ratio	2.5
Heat exchanger temperature difference	10 ^{0}C
Temperature difference of each effect of MED	5 ^{0}C
Evaporation Temperature	1.5 ^{0}C
Condenser temperature difference	5 ^{0}C

Table 2. Result of thermodynamic modeling for proposed system

Number of Stream	**T (^{0}C)**	**P (kPa)**	**h (kJ/kg)**	**S (kJ/kgK)**	**E^{total} (kJ/s)**
1	34.6	0.6812	93.07	0.1977	283.6
2	34.6	7.424	97.19	0.1977	287.7
3	67.6	7.424	159	0.3989	289.5
4	80	7.424	185.6	0.4665	553.3
5	45.62	7.424	123.2	0.264	551.3
6	35.62	0.6812	123.2	0.202	569.7
7	80	7.424	2649	8.481	126.6
8	40.11	7.424	168	0.5737	1.486
9	1.5	0.6812	168	0.6116	9.795
10	1.5	0.6812	2503	9.114	208.3
11	87.25	101.3	361.2	5.886	5.729
12	25	101.3	298.6	5.695	0.0211
13	35	101.3	146.7	0.5049	-
14	25	101.3	104.8	0.3669	-
15	25	101.3	104.8	0.3669	-
16	30	100	125.8	0.4365	-
21	150	101.3	424.8	6.049	-

Table 2. Result of thermodynamic modeling for proposed system (cont.)

Number of Stream	**T (ºC)**	**P (kPa)**	**h (kJ/kg)**	**S (kJ/kgK)**	**Etotal (kJ/s)**
22	130	700	470.8	1.772	41.92
25	105	280	455.5	1.779	24.47
26	29.93	150	125.5	0.4355	1394
27	59.93	150	251	0.8302	1402
28	59.23	280	262.5	1.206	2.222
29	25	101.3	99.01	0.3459	0
30	49.23	101.3	195.4	0.657	3.682
31	35	280	236.7	1.125	0.3335
32	35.28	700	237.1	1.126	0.6306
33	133.3	297.9	2725	6.994	645.1
34	99.86	100.8	2675	7.356	487.8
35	99.05	101.3	388.9	1.21	31.27
36	133.3	297.9	560.6	1.67	67.55
37	138.9	350	2732	6.939	668.3
38	99.86	100.8	418.5	1.305	33.99
39	99.72	100.3	2675	7.358	487.1
40	98.63	101.3	379.6	1.175	30.91
41	99.72	100.3	417.9	1.304	33.87
42	99.58	99.8	2675	7.36	486.4
43	98.1	101.3	367.7	-	30.83
44	99.58	99.8	417.3	1.302	33.75
45	99.44	99.3	2675	7.361	485.7
46	99.44	99.3	2675	7.361	485.7
47	99.44	99.3	2675	7.361	485.7
48	99.44	99.3	2227	6.16	396.1
50	25	350	105.1	0.3669	0.2494
51	89.44	350	374.8	1.186	25.91
52	25	101.3	104.8	0.3669	-

Based on these data, the performance of the system is evaluated and is presented in Table 3. The mentioned exergy balance is applied for each component of the system and the exergy destruction rate and exergy efficiency system components are shown in Table 4.

Table 3. Performance of the system

Parameters	values
Thermal efficiency	61 %
Exergy efficiency	7%
Cooling load	5658 KW
Heating load	10391 KW
Power	802.5 KW
Fresh water	9.328 Kg/s

Figure 2, shows the amount of exergy destruction for some components of system which has the considerable share in total exergy destruction of the system in comparison to others. As it is shown, biomass burner (21539KW), ETC (9829KW) and vapor generator (741.7 KW)are the major sources of exergy destruction rate. In the biomass burner, the irreversibility is because of occurring combustion in it and combustion is one of the sources of irreversibility in a process. In the ETC, the irreversibility created is due to large temperature difference between solar heat and fluid in the tubes. The main reason of irreversibility in vapor generator is related to the stream-to-stream heat transfer. Since the amount of irreversibility of remaining components is negligible, their exergy destruction is not considered here.

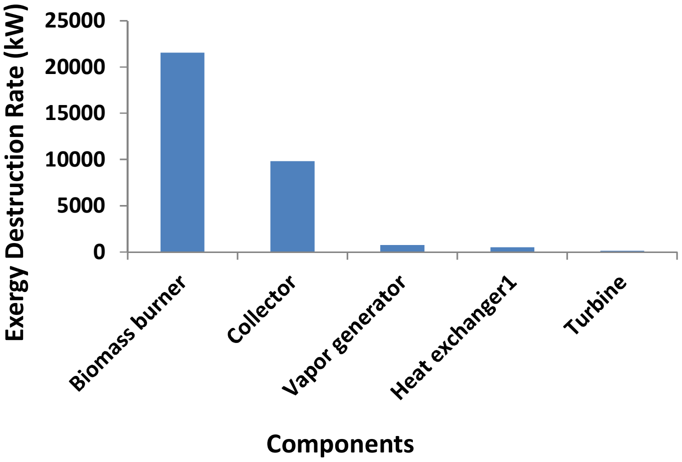

Figure 2. Some selected components exergy destruction rate (kW)

Three independent variables including turbine inlet temperature, turbine inlet pressure and Heat Exchanger1 temperature difference are varied to investigate their effects on system total exergy efficiency and is illustrated in Figure 3, 4,5.

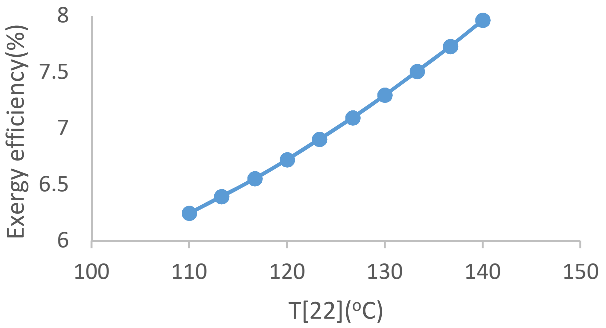

Figure 3. Effect of turbine inlet temperature on exergy efficiency

Figure 3 demonstrates the effect of turbine inlet temperature on exergy efficiency of the system, by increasing turbine inlet temperature between 110 C and 140 C exergy efficiency increases about 27%.

The effect of variation of turbine inlet pressure on exergy efficiency of the system is shown in Figure 4,as turbine inlet pressure varies between 650 kPa and 800 kPa, exergy efficiency of the system decreases about 5%.This decrement is due to decrement of amount of electricity and heating power produced by multigeneration system.

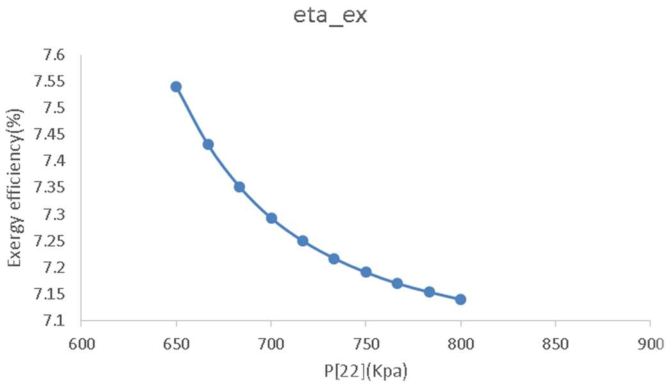

Figure 4. Effect of turbine inlet pressure on exergy efficiency

Figure 5 represent the effect of Heat Exchanger1 temperature difference on the exergy efficiency of the system, as it can be observed by increasing heat exchanger1 temperature difference between 5 and 15, exergy efficiency of the system decreases because of increment in total exergy destruction of the system.

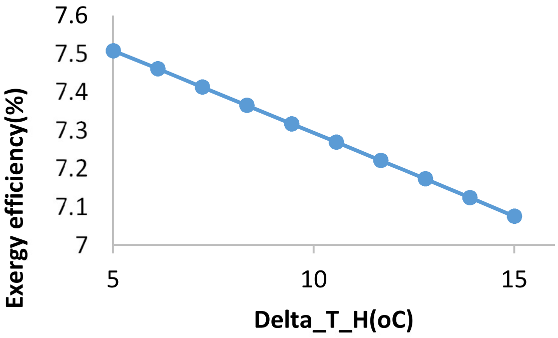

Figure 5. Effect of temperature difference of heat exchanger1 on exergy efficiency

OPTIMIZATION

Optimization is carried out to determine the best design parameters of the system and different objectives can be defined for this purpose. For this purpose genetic algorithm (GA) through EES software is used for optimization of CCHP hybrid desalination plant. The selected decision variables are turbine inlet temperature (T[22]), turbine inlet pressure (P[22]) and Temperature difference of Heat Exchanger1(ΔT_{HE1}). Table 4 shows the base case and optimal case values of the decision variables and objective functions.

Table 4. Exergy destruction rate and exergy efficiency of some system components

Component	**Exergy destruction rate (** $E\dot{x}_D$ **)**	**Exergy efficiency (** ε **)**
Turbine	$E\dot{x}_{D,turb} = (E\dot{x}_{22} - E\dot{x}_{25}) - \dot{W}_{turb}$	$\varepsilon_{turb} = \frac{\dot{W}_{turb}}{(E\dot{x}_{22} - E\dot{x}_{25})}$
Heat Exchanger1	$E\dot{x}_{D,HE1} = (E\dot{x}_{25} - E\dot{x}_{28}) - (E\dot{x}_{27} - E\dot{x}_{26})$	$\varepsilon_{HE1} = \frac{(E\dot{x}_{27} - E\dot{x}_{26})}{(E\dot{x}_{25} - E\dot{x}_{28})}$
Pump1	$E\dot{x}_{D,pump\,1} = \dot{W}_{pump\,1} - (E\dot{x}_{32} - E\dot{x}_{31})$	$\varepsilon_{pump1} = \frac{(E\dot{x}_{32} - E\dot{x}_{31})}{\dot{W}_{pump_1}}$
Preheater	$E\dot{x}_{D,PH} = (E\dot{x}_{48} - E\dot{x}_{47}) - (E\dot{x}_{52} - E\dot{x}_{51})$	$\varepsilon_{PH} = \frac{(E\dot{x}_{52} - E\dot{x}_{51})}{(E\dot{x}_{48} - E\dot{x}_{47})}$
Collector	$E\dot{x}_{D,coll} = E\dot{x}_s - (E\dot{x}_{37} - E\dot{x}_{52})$	$\varepsilon_{D,coll} = \frac{(E\dot{x}_{37} - E\dot{x}_{52})}{E\dot{x}_s}$
Ejector	$E\dot{x}_{D,ejc} = \dot{m}_{37}(ex_{37} - ex_{33}) - \dot{m}_{46}(ex_{33} - ex_{46})$	$\varepsilon_{ejc} = \frac{\dot{m}_{46}(ex_{33} - ex_{46})}{\dot{m}_{37}(ex_{37} - ex_{33})}$
Absorber	$E\dot{x}_{D,abs} = (E\dot{x}_{10} + E\dot{x}_1 - E\dot{x}_6) - (E\dot{x}_{13} - E\dot{x}_{14})$	$\varepsilon_{abs} = \frac{(E\dot{x}_{13} - E\dot{x}_{14})}{(E\dot{x}_{10} + E\dot{x}_1 - E\dot{x}_6)}$
Evaporator	$E\dot{x}_{D,eva} = (E\dot{x}_9 - E\dot{x}_{10}) - E\dot{x}_{Q,eva}$	$\varepsilon_{eva} = \frac{E\dot{x}_{Q,eva}}{(E\dot{x}_9 - E\dot{x}_{10})}$

Table 5. Base case and optimal case values of the decision variables and objective functions

Parameters	Base case	Optimal case
Exergy efficiency (%)	7	8.5
Turbine inlet pressure (kPa)	700	657.5
Turbine inlet temperature (ºC)	130	137
Temperature difference of Heat Exchanger.1 (ºC)	10	5

CONCLUSION

The present work proposes a biomass and solar based CCHP hybrid desalination system which produces power, cooling, heating and fresh water. Energy and exergy analysis is applied to identify the components with high exergy destruction rate and calculate the exergy efficiency of the system. Results show that biomass burner, evacuated tube solar collectors and vapor generator are the major sources of exergy destruction thus it is necessary to have better design for these components to minimize the system exergy destruction. By increasing turbine inlet temperature, decreasing Turbine inlet pressure and decreasing Temperature difference of Heat Exchanger.1 exergetic performance of the system improves. The exergy efficiency is 7%.Optimization is carried out through EES software using GA and results show that exergy efficiency in optimum case improves 21% in comparison to base case value.

NOMENCLATURE

A_{coll}	Solar collector area, m^2
Ex	Specific exergy, kJ/kg
$\dot{Ex}$	Exergy, kW
G_t	Total instantaneous radiation, W/m^2
H	Specific enthalpy, kJ/kg
In	Inlet
$\dot{m}$	Mass flow rate, kg/s
out	Outlet
P	Pressure, bar
$\dot{Q}$	Heat transfer rate, kW
R	Gas constant, kJ/kgK
s	Specific entropy, kJ/kgK
T	Temperature, ºC
$\dot{W}$	Work rate, kW
x_k	Number of molecules of gas k molecules

Subscripts

0	Ambient
ch	Chemical
D	Destruction
HHV	Higher Heating Value
ph	Physical
Turb	Turbine

Greek symbols

ε	Exergy efficiency

Abbreviations

CCHP	Combined Cooling, Heating and Power

EES	Engineering Equation Solver
ORC	Organic Rankine Cycle

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