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RESEARCH NOTE

The Energy and Exergy Analysis of Integrated Hydrogen Production System Using High Temperature Steam Electrolysis with Optimized Water Path

H. Raeissi Jelodar[a], G. R. Salehi*[b], R. Abedini[c]

[a] *Department of Energy Systems Engineering, Petroleum University of Technology, Mahmoodabad, Iran*
[b] *Department of Mechanical Engineering, Petroleum University of Technology, Abadan, Iran*
[c] *Department of Process, Faculty of Chemical Engineering, Babol Noshirvani University of Technology, Babol, Iran*

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ABSTRACT

In this research, solar-drived integrated Hydrogen production (HP) using high-temperature steam electrolysis (HTSE) is thermodynamically evaluated. This system includes an organic Rankine cycle (ORC), Rankine cycle, Brayton cycle, solar tower, and High Temperature Steam Electrolysis (HTSE). Solar energy supplies thermal energy. This heat source is applied for generating power. This energy is used for HTSE due to its demand in the form of electricity. First, we calculated inlet and outlet energy and their rates for whole subsystems. The results showed 50.77% overall and 31.63% exergy efficiencies related to power generation section and 92.85% overall energy and 91% exergy efficiencies related to hydrogen production section. Also in this research we found the importance of auxiliary equipment. Auxiliary equipment helps that significant amount of hydrogen production to be saved. This amount at 577 K is equal that produces 0.093 kg H_2/s

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NOMENCLATURE

$\dot{m}$	Mass flow rate, kg/s	NOH	Number of heliostats
h	Enthalpy, kJ/kg	*TAOH*	Total area of heliostats, m^2
P	Pressure, kPa	WF	Working fluid
T	Temperature, K	CR_{Br}	Compression ratio
C_p	Constant pressure	TPC	Turbine power capacity
C_v	Constant volume	TIT	Turbine inlet temperature
k	Special heats coefficient	TEP	Turbine exit pressure
LHV	Low heating value, kJ/kg	$\dot{E}x^Q$	Exergy due to heat transfer
y_i	Mole fraction	$\dot{E}x^W$	Exergy from work

1. INTRODUCTION

The world's dependence on fossil fuels to supply energy to industies, transportation sectors, power generation and buildings has sharply increased since the industrial revolution. Indeed, the life standards have increased as well as energy consumption and the use of renewable energy is very important in replacement of fossil fuels [1]. However, some concern such as, climate change, global warming, acid rains, pollution, melting of ice caps, sea levels increasing and ozone layer depletion causd by excess utilization of fossil fuel in different approaches [2] and alternative energies became much more important [3]. Hydrogen has been considered by researchers as an alternative renewable and clean energy resource in different approaches, from methanol production [4] to pure and or fuel additive in internal combustion engines [5]. Although hydrogen abundantly exists in the earth, it is just found in composition of other materials [6]. In consequent, hydrogen production (HP) is now one of the most interesting field of study and extended works were conducted to improve its

*Corresponding Author Email: *rezasalehi20@gmail.com* (G. R. Salehi)

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efficiency economically [7-9]. The efforts of HP from renewable sources, as sustainable hydrogen economy, can be categorized in two main groups; low and high temperature electrolyzing. High temperature electrolysers are more advantageous than low temperature ones due to fast electrochemical reactions and good ion conduction at high temperatures [10, 11], while they need more inlet power and heat. Demanded heat and power can be provided by different thermodynamic cycles employing solar [12], wind turbine [13], nuclear [14] and geothermal [15] energy technologies. The overall solar based proposed system by Ozcan and Dincer [16] had 18.8% energy and 19.9% exergy efficiencies, respectively. They have assert that these efficiencies can be improved to 26.9% and 40.7% employing heat absorbed by the molten salt as a main energy input to the system. They also reported that the highest rate of exergy destruction occurs in the solar system, accounting for 79% of the total exergy destruction of the system. Upon dividing solar-based/ production sections, Balta et al. [17] reported that the exergy and energy yield of power generation system (PGS) are found 22.36 and 24.79% , respectively. Also, the exergy and energy yield for HP system were 87 and 88%, respectively. Moreover, one required a conceptual design solar energy photovoltaic conversion to HP from electrolysis of alkaline water. The other new application of the solar energy such as free piston Stirling engine and thermo-acoustic engines accomplished by Tavakolpour et al. [18-20]. A gamma-type, low-temperature differential (LTD) solar Stirling engine with two cylinders was modeled [18-21]. The indicated power at 30 rpm was computed to be 1.2W. In this paper, a HTSE is employed for hydrogen production and a Brayton cycle integrated by solar energy is used to provide electrolyser demanded heat and power. A Rankine and organic Rankine cycles (ORC) are also utilized for system performance enhancement and in addition to compare two working fluids of ORC, first and second law analysis of proposed system were onducted to find out the best operation condition.

2. SYSTEM DEFINITION

The proposed hydrogen production system has two main parts, namely hydrogen production and power generation. Hydrogen production section is adapted from literature [22] that is HP via HTSE method where the high temperature steam is divided into pure hydrogen and oxygen by received electricity from PGS. Demanded heat is also provided from waste heat of PGS. Indeed, two heat exchangers are also utilized to use the heat of separated hot hydrogen and oxygen as shown in Figure 1.

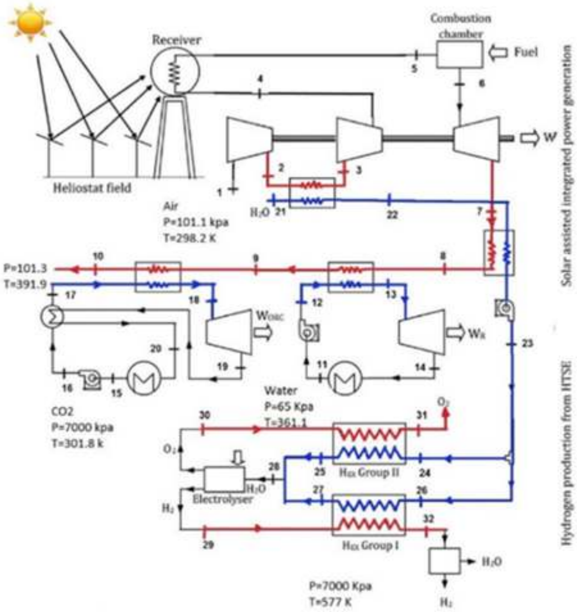

Figure 1. The schematic diagram of the proposed system

Power generation section (PGS) consists of three cycles, namely, Brayton, Rankine and ORC. The main demanded power and heat for electrolyser is produced by Brayton cycle. In this cycle, air is compressed in

two-stage compressor via inter-cooler which makes air temperature near to ambient temperature. Electrolyser feed water is pre-heated by inter-cooler waste heat absorption. Then compressed air is pre-heated in solar receiver and more heat is added to achieve the highest feasible temperature due to the thermal resistant of turbine blades in combustion chamber. The energy restored in the air stream is first change to the power via turbine and second absorbed by pre-heated electrolyser feed water. In the following, extra energy of air is employed to run Rankine and ORC boilers, respectively. Finally, a simple Rankine cycle and an ORC with regenerator are utilized to convert air extra energy to power. The general characteristics of integrated system are summarized in Table 1.

HTSE is still in its early stage of growth. HTSE is a very promising way of producing hydrogen. From the thermodynamic point of view, water breakup is more beneficial for the electrolysis of water at high temperatures (800-1000˚C), because is energy supplied in the form of a mixture of heat and electricity. The solar tower model is adopted by Quero et al. [17] and Joshi et al. [23]. There are various types of HP methods such as solar thermal, photovoltaic, photoelectrolysis, biophotolysis. They performed a brief study of various hydrogen production processes and compared solar-based hydrogen production processes with regard to exergy efficiency and sustainability.

TABLE 1. General characteristics of the proposed system

Solar tower	
RH	65 m
NOH	69
TAOH	8349 m^2
Brayton Cycle	
WF	Air
η_{IT}	0.92
η_{IC}	0.88
CR_{Br}	11.2
TPC	5670 kW
Rankine Cycle	
WF	Water
η_{IT}	0.91
η_{IP}	0.88
TIT	623.15 K
TIP	3000 kPa
TEP	65 kPa
TPC	1020 kW
ORC	
WF	CO2
η_{IT}	0.95
η_{IP}	0.90
TIT	453.15 K
TIP	15000 kPa
TEP	7000 kPa
TPC	445 kW

Quero et al. [17] investigated a receiver that was mounted at the top of the tower at an altitude of 65 meters and the space of the heliostat is 8350m^2. Initially, the compressed air in the solar tower receiver is heated to 1078.15K and then enters to the combustion chamber. Natural gas is used for the combustion process, and the air heats up to its final temperature before entering the gas turbine. gas turbine selected model is Taurus model from solar Turbines [17, 24]. It has a compression ratio of 11.2, with a capacity of 5670 kW. The main advantage of gas turbine is its compact design. The exhaust gases from the turbine then pass through three heat exchangers to supply heat-to-water supply for the HP process, the Rankin cycle and the transferring ORC. The Rankin cycle works with water as a liquid and has a capacity of 1020 kW. The last ORC cycle that works as a fluid. ORC is a method of using low temperature heat; Energy transformation technology is promising and can increase energy by converting heat into electrical energy. In the system, the R744 fluid is pumped from the condenser using a liquid pump and its thermal energy is received from the heat exchanger and liquid switched to superheated steam. The superheated steam then enters the turbine and expands to low pressure. At the outlet of the ORC turbine, the R744 steam enters to recuperator for preheating of the R744 after pumping process. Subsequently, the turbine exhaust is exacerbated by a cooling tower for extraction of heat into the liquid medium at the condenser. The general properties of the solar energy system are presented in Figure 1. To analyze the proposed system performance, the energy and exergy equations of each cycle components should be separately applied. In this section, the required equations are introduced. To simplify the modeling, the following assumptions are used:

- All sections (Brayton cycle, Rankine cycle, ORC, and electrolyser) are Steady State Steady Flow (SSSF) process.
- Air and combustion products considered as ideal gases.
- Methane used as fuel in the combustion chamber.
- Condensers outflow considered as saturated liquid in the Rankine and ORC cycle.
- The properties of CO_2 and water are Compatible from thermodynamic tables.

3. ENERGY ANALYSIS

Given the assumption mentioned to diescribe the mathematical model, the energy equation and mass conservation law for each camponent as SSSF process [25].

$$\sum \dot{m}_e = \sum \dot{m}_i \tag{1}$$

$$\dot{Q} - \dot{W} = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i \tag{2}$$

where, h and m˙ refer to the enthalpy and mass flow rate, respectively. Also, subscripts e and i refer to exhaust and inlet conditions.

Generating power of three cycle is the total power generated and consumed by compressors, turbines and pumps. The thermal efficiency is the ratio of production to the heat of the input. For example, in the brayton cycle:

$$\dot{W}_{net} = \dot{W}_{GT} + \dot{W}_{comp1} + \dot{W}_{comp2} \tag{3}$$

$$\dot{Q}_{net} = \dot{Q}_{receiver} + \dot{Q}_{C.Ch} \tag{4}$$

$$\eta_I = \frac{\dot{W}_{net}}{\dot{Q}_{net}} \tag{5}$$

The mass flow rate required for fuel consumption, the ORC and Rankin cycle, and the HP supply feedwater are calculated from the temperature gradient generated on the hot side of the heat exchangers. Assuming the heat exchangers are insulated, we must have:

$$\dot{m}_{air}C_p(T_6 - T_5) = \dot{m}_{fuel}\eta_{comb}LHV \quad (6)$$

$$\dot{m}_{air}C_p(T_8 - T_7) = \dot{m}_{water}(h_{22} - h_{23}) \quad (7)$$

$$\dot{m}_{air}C_p(T_9 - T_8) = \dot{m}_{Rankine}(h_{12} - h_{13}) \quad (8)$$

$$\dot{m}_{air}C_p(T_{10} - T_9) = \dot{m}_{Rankine}(h_{17} - h_{18}) \quad (9)$$

where, LHV and η_(comb) are the low heating value of fuel and combustion efficiency, respectively; which are considered by 0.98 and 47.13 MJ/kg [26].

4. EXERGY ANALYSIS

Analysis of the second law of each component is possible after applying the first law and calculating the thermodynamic properties of the fluid. To achieve this, the exergy equilibrium is used, for example:

$$\dot{Ex}^Q + \sum \dot{m}_i ex_i = \dot{Ex}^W + \sum \dot{m}_e ex_e + I \quad (10)$$

where, ex, $\dot{Ex}^W$, $\dot{Ex}^Q$ and I refer to exergy due to exergy destruction, exergy from work, specific exergy and heat transfer, respectively. Total exergy consists of chemical and thermo-mechanical exergy and is stated as follows:

$$ex = ex_{tm} + ex_{ch} \quad (11)$$

$$ex_{tm} = (h - h_0) - T_0(s - s_0) \quad (12)$$

$$ex_{ch} = \sum_{i=1}^{N} y_i ex_i^{ch} + RT_0 \sum_{i=1}^{N} y_i \ln(y_i) \quad (13)$$

y_i refers to the mole fraction of flu composition. s Refers to entropy and index 0 refers to the dead state, working fluids in ambient pressure and temperature. The fuel exergy is also calculated from the semi-empirical equation [27]:

$$\epsilon = \frac{ex_{fuel}}{LHV_{fuel}} \quad (14)$$

The value of ε is close to the unit. Exergy transmission due to work and heat through the borders is:

$$\dot{Ex}^W = \dot{W} \quad (15)$$

$$\dot{Ex}^Q = \left(1 - \frac{T_0}{T_s}\right)\dot{Q} \quad (16)$$

where, T_s is the source temperature. The effectiveness of the second law as a more precise criterion for the functioning of the system is defined, as the division of exergy to the consume one:

$$\eta_{II} = \frac{Ex_{net}}{Ex_i - Ex_e} \quad (17)$$

For HP performance analysis, first law efficiency is defined as the ratio of LHV of separated hydrogen from feed water to heat entered to the system. For second law efficiency, separated hydrogen exergy is compared via inlet exergy:

$$\eta_I = \frac{\dot{m}_{H_2,Sep} * LHV_{H_2}}{Q_{in}} \quad (18)$$

$$\eta_{II} = \frac{Ex_{H_2,Sep}}{Ex_{in}} \quad (19)$$

5. RESULTS AND DISCUSSION

5. 1. Validation The integrated solar system for sustainable HP was investigated via HTSE method. The system was analyzed based on the model and hypotheses. In this analysis, we examine the system using the governing equations of total mass, energy, and exergy. For analyzing and applying thermodynamic equations at a temperature of 25°C and a pressure of 101kPa, EES software was used. The proposed cycle in this research is a new idea. Therefore, there are no experimental data for validating the model results. So, each cycle is confirmed separately with the previous study [17] as reported in Table 2. Since the accuracy of the model is within the acceptable range, it can be stated that the results from the production model are reliable.

5. 2. Results of Analysis The thermodynamic characteristics of the fluid in each vapor reported in Table 3. Using these data and the equations defined in the description section of the model is defined, the system performance is summarized in Table 4.

The power generation capacity of the Brayton, Rankine and ORC cycles was reported in Table1. As a result, the total electricity generated by three cycles for the production of hydrogen is 8873 kW. According to the analysis, Brayton cycle efficiency was 43.1% while the efficiency of the Rankine cycle was 24.23% and the ORC cycle was 19.81%. For the analysis of the second

TABLE 2. Validation of simulation data

cycle	energy efficiency		exergy efficiency		$\frac{\dot{m}_{H2,prod.}}{\dot{m}_{H2,int.}}$ %	
	ref [17]	Sim.	ref [17]	Sim.	ref [17]	Sim.
Brayton	38.7	38.5	47.7	50.7	-	-
Rankine	24.2	24.2	40.1	63.7	-	-
ORC	25.2	25.2	40.5	32.5	-	-
Simple PGS	24.7	24.6	22.3	27.1	-	-
Simple HTSE	-	30.9	-	0.39	66.6	65.4

TABLE 3. each steam characteristics of proposed system

State NO	fluid	$T\ [K]$	$P\ [kPa]$	$\dot{m}\ [kg/s]$	$h\ [kJ/kg]$
1	Air	298.2	101.3	14.24	298.6
2	Air	434.9	339	14.24	436.4
3	Air	298.2	1135	14.24	298.6
4	Air	434.9	135	14.24	436.7
5	Air	903.6	1135	14.24	937.2
6	Air	1523	101.3	14.24	1664
7	Air	833.2	101.3	14.24	858.9
8	Air	795.4	101.3	14.24	777.8
9	Air	1023	101.3	14.24	1072
10	Air	1101	65	14.24	1163
11	H_2O	361.1	30000	1.528	368.5
12	H_2O	361.4	3000	1.528	371.9
13	H_2O	623.2	65	1.528	3115
14	H_2O	361.1	7000	1.528	2447
15	CO_2	301.8	15000	9.221	-213.9
16	CO_2	320.4	15000	9.221	-201.1
17	CO_2	367.1	15000	9.221	-58.1
18	CO_2	453.1	7000	9.221	81.55
19	CO_2	383.4	7000	9.221	33.3
20	CO_2	303.7	101.1	9.221	109.7
21	H_2O	298.2	101.1	0.85	104.8
22	H_2O	373.1	101.1	0.85	2418
23	H_2O	905.1	101.1	0.85	3776
24	H_2O	905.1	101.1	0.28	3776
25	H_2O	1185	101.1	0.28	4426
26	H_2O	905.1	101.1	0.57	3776
27	H_2O	1185	101.1	0.57	4426
28	H_2O	1185	101.1	0.85	4426
29	H_2	1233	10000	0.093	12881
30	O_2	1233	10000	0.7464	966.3
31	O_2	569	7000	0.7464	258.14
32	H_2	577	7000	0.093	3913

law, the exergy efficiency of Brayton, Rankine and ORC cycles has been reported to be 57.42, 46.41and 45.72%, respectively. The exergy rate of destruction for three Brayton, Rankine and ORC cycles is 29700, 616.6 and 325.4 kW, respectively. Also, the exergy rate for

TABLE 4. proposed system performance

Parameter	Value
Net power	8873 kW
Net irreversibility	32.65 kW
consumed fuel	1.14 kg/s
Produced H_2	0.09 kg/s
$\eta_{I,PGS}$	50.7 %
η_{I,H_2}	98.3 %

system PG degradation is 30642 kW. The overall exergy and energy efficiency of the PGS is 31.63 and 50.77%, respectively. For the HTSE hydrogen production section, energy and exergy efficiency results are 92.85 and 91.01%, respectively, which is higher than the previous HTSE hydrogen production models. Increasing the efficiency due to the change in the direction of the inlet water into the electrolyser, causes an increase of inlet steam temperature. The results showed that without the auxiliary facilities, the hydrogen produced at a temperature of 577K is 0.093kg/s. This amount of hydrogen compared to the amount of hydrogen produced in previous studies of hydrogen production by HTSE method has a remarkable advantage.

The effects of the temperature and pressure inlets on the turbine of the Brayton cycle have been specifically analyzed from the PG section. To determine the effect of system parameters on exergy degradation, system power and energy efficiency in Brayton cycle and the PG section as well as the hydrogen production efficiency for a specific case, we study the results of the, Brayton cycle by changing the pressure and temperature. Upon increasing turbine inlet temperatures from 1,400 to 1,600 k, turbine power increases, which increases energy efficiency, exergy and exergy degradation. However, an increase in the exergy increase in exhaust emissions is less than the energy efficiency and exergy.

Proposed system performance due to the change of Brayton turbine inlet temperature, when the other inlet parameters were considered to be constant, are shown in Figure 2. Demanded Figure 3 proposed system performance due to the change of Brayton turbine inlet temperature. Fuel was increased 36.8% to achieve 1600 K, while the heat received from the sun had no change. Consumed fuel enhancement rate was greater than turbine out power one, so the ratio of powers to added heat in combustion chamber was slightly decreased. Furthermore, the irreversibility of general system was increased due to the more temperature of heat transfer in heat exchangers and hydrogen production efficiency was decreased by 6% due to the fuel consumption increase caused by turbine inlet temperature enhancement. System response to input heat flux from the sun is shown in Figure 3 and considering fixed turbine inlet temperature, less fuel is needed when the input heat flux was increased. Consequently, the ratio of produced power and hydrogen to consumed heat in combustion chamber were increased by 29 and 13%, respectively. Produced power and efficiency of Brayton cycle are affected by compression ratio and to investigate its effect on system performance it was changed between 810 and 1600 kPa. In Figure 4, first and second law efficiencies, produced power and irreversibility of Brayton cycle via compression ratio changes were shown. All of them were increased by compression ratio enhancement due to more turbine power generation rate than compressor power consumption rate. Irreversibility was also increased due to the enhancement of mean working pressure of cycle. Considering Brayton cycle as the main PG core of PGS, total power was increased as well as Brayton cycle.

To investigate the role of working fluid on ORC performance, its energy and exergy parameters are compared employing two different working fluids namely, carbon dioxide (R744) and ammonia (R717) which are shown in Figure 5. In case of using carbon dioxide as working fluid, less net power was achieved and irreversibility decreased noticeably. The interaction of less power and irreversibility caused both more energy and exergy efficiencies when carbon dioxide employed as working fluid.

The total amount of energy received, the process of hydrogen production and power generation is 17467 kW. This amount of energy comes from solar energy and burning natural gas in the combustion chamber. The energy used to run two Rankin, ORC, and also Electrolyzer devices. Respectively, the energy required for the ORC cycle, the Rankin and the Electrolyzer is 1288, 4191, and 1154 kW, respectively. The amount of 1334.3 kW of energy from point 10 enters the environment, which is suitable for heat stove design (Figure 6).

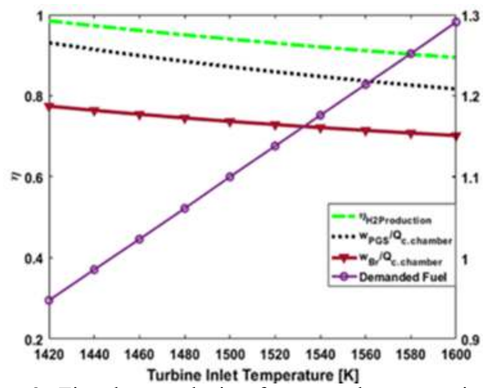

Figure 2. First law analysis of proposed system via turbine inlet temperature

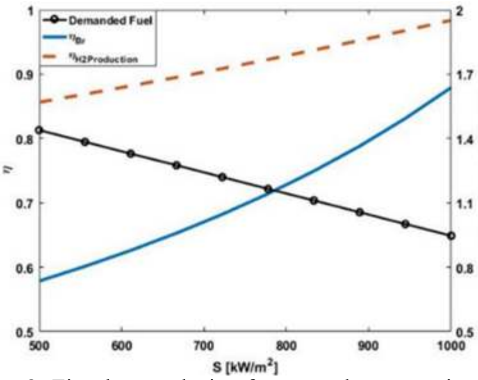

Figure 3. First law analysis of proposed system via sun heat flux

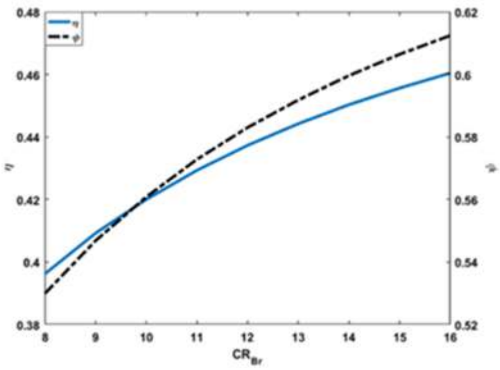

Figure 4. First and second law efficiencies of Brayton cycle

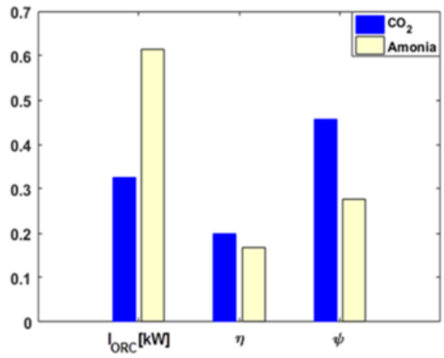

Figure 5. Irreversibility, energy and exergy efficiencies of ORC via ORC working fluid

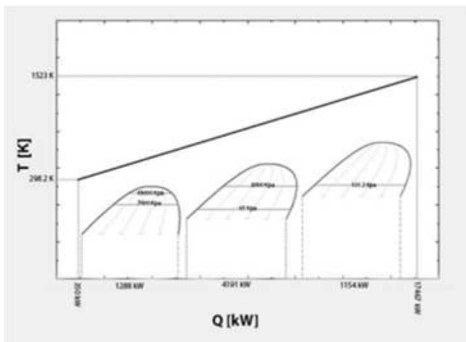

Figure 6. The amount of energy received by the cycle ORC, Rankin and electrolyzer is generated from the total energy

6. CONCLUSION

In this research we compared production of sustainable hydrogen with HP by HTSE thermodynamically. Here we use this electrolysis system for producing hydrogen. This system need heat energy. In order to this demand, the applied power generation system supply heat energy by producing electricity and exhaust gases the total electricity generated by three cycles for the production of hydrogen is 8873kW. In order to achieve our objective, we calculated system efficiencies and rates of exergy destruction by analyzing system's energy and exergy. Results showed that in power generation system including solar tower, the total rate of exergy destruction is equal to 30642kW. The main factor of this result was tower system because of heliostat field area's number and transfer process. Also, the efficiency of total energy for PGS was 50.77% while it was 92.85 for hydrogen production and the efficiency of total exergy for power generation was 31.63% while it was 92.85% for hydrogen production. Moreover, we analyzed system performance parametrically and also we obtained 0.093 kg H_2/s. Our research should investigate problems more about maintaining greener energy. Finally, we suggest that in future studies, it's better to focus on progressing, installing and modeling about systems of sustainable hydrogen production.

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The Energy and Exergy Analysis of Integrated Hydrogen Production System Using High Temperature Steam Electrolysis with Optimized Water Path

RESEARCH NOTE

H. Raeissi Jelodar[a], G. R. Salehi[b], R. Abedini[c]

[a] *Department of Energy Systems Engineering, Petroleum University of Technology, Mahmoodabad, Iran*
[b] *Department of Mechanical Engineering, Petroleum University of Technology, Abadan, Iran*
[c] *Department of Process, Faculty of Chemical Engineering, Babol Noshirvani University of Technology, Babol, Iran*

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چکیده

در این تحقیق، تولید هیدروژن مجتمع شده با انرژی خورشیدی (HP) با استفاده از الکترولیز بخار با درجه حرارت بالا (HTSE) ، ارزیابی ترمودینامیکی می شود. این سیستم شامل یک چرخه رانکین آلی (ORC)، چرخه رانکین، چرخه ی برایتون، برج خورشیدی و الکترولیز بخار با درجه حرارت بالا (HTSE) می باشد. انرژی خورشیدی تامیین کننده انرژی حرارتی می باشد.این انرژی حرارتی برای تولید نیرو اعمال می شود. این انرژی به دلیل تقاضای آن به شکل برق مورد استفاده قرار می گیرد. اول، ما انرژی ورودی و خروجی و نرخ های آنها را برای زیر سیستم های کل محاسبه کرد. نتایج به دست آمده حاوی ۵۰,۷۷٪ کل انرژی و ۳۱,۶۳٪ بهره وری از اگزرژی مربوط به بخش تولید برق و ۹۲,۸۵٪ انرژی کلی و ۹۱,۰۱٪ بهره وری از اگزرژی مربوط به بخش تولید هیدروژن است.همچنین در این تحقیق ما اهمیت تجهیزات کمکی را در بر داشتیم. تجهیزات کمکی کمک می کند که مقدار قابل توجهی تولید هیدروژن ذخیره شود. این مقدار برابر با ۵۷۷ کیلوگرم است که ۰،۰۳ کیلوگرم بر ثانیه H_2 تولید می کند.

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