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Developing a tri-generation system of power, heating, and freshwater (for an industrial town) by using solar flat plate collectors, multi-stage desalination unit, and Kalina power generation cycle

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ABSTRACT

In this paper, an integrated structure of cogeneration and freshwater production for residential complexes usage in an industrial town of Assaluyeh, in south of Iran and besides to the Persian Gulf is developed and analyzed. In this process, solar flat plate collectors on the house's roof to provide the required thermal energy, Kalina cycle to generate integrated power and a multi-stage desalination process for the freshwater production of residential complexes, are utilized. The proposed system is simulated through TRNSYS, HYSYS, and MATLAB Software. This integrated structure has the capability of simultaneous production of 1869 kW power, 65194 kW heating and 83.22 kg/s freshwater for residential complexes. Based on the results the integrated structure has a total thermal efficiency of 44.64% and a total exergy efficiency of 90.04%. Exergy analysis shows that the highest amount of exergy destruction on a specific day of the year, the percentage of the destructed exergy from the input exergy flow, occurs in the solar flat collectors and the auxiliary boiler, 54.72%, 21.89%, respectively. By sensitivity analysis of the important indices for the developed integrated structure, including the number of collectors, the mass flow rate of the collector and the molar composition of the Kalina power generation cycle, an appropriate solution is proposed to improve the modeling effective parameters.

1. Introduction

Increase in industrial growth and population, highlighted the need of supplying sufficient energy demand and enough fresh water for human activities [1]. Utilization of the renewable energies sources is considered as a sustainable solution for addressing the energy and freshwater production requirements. Combining renewable energy plants and freshwater production unit is a suitable design for sustainable development [2,3]. For designing and developing renewable power production plants, several parameters should be considered. Besides the geographical potential availability, closeness to consumers, commodities production capabilities such as freshwater, heating or electricity should also be considered [4].

Solar energy is a proper solution for providing thermal energy and electricity [5]. Solar energy utilization in industry sector is an attractive concept. Because this free energy source has the potential to provide the industrial energy demands. Solar energy can be used separately to satisfy industry demands. There are several types of solar energy systems which can be useful for industry. Solar energy can be utilized through several methods such as photovoltaic panels which generate directly the required electricity and solar thermal systems which can be applied to thermal processes. Solar systems have this advantage to combine with other systems like desalination and power generation [6]. Developing a multi-commodity system by using solar energy as a driving force to produce commodities such as freshwater, electricity, and heat could be a sustainable approach for societies [2]. Solar based multi production systems have this advantage to generate more commodities without any paid cost for the needed initial energy source and also results higher efficiency for the system in comparison to single generation systems [7].

The solar energy can be harnessed by several solar systems. the simplest solar device is a solar collector [8]. Solar flat collectors firstly developed by Hottel and Woertz [9] in 1942.

Desalination systems are classified according to the required energy source (thermal, mechanical, electrical, and chemical). In thermal energy required type, the seawater is distilled by a thermal energy source. This thermal energy might be supplied from the conventional fossil fuel sources or from a renewable energy source such as solar energy or

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Nomenclature

E	specific flow exergy (kJ/kg mole)
F	produced freshwater (kg/s)
Ex	exergy (kW)
$\dot{m}$	mass flow rate (kg mole/s)
H	enthalpy (kJ/kg mole)
P	pressure (kPa)
$\dot{Q}$	collected heat (kW)
T	temperature (°C)
W	work (kW)
S	entropy (kJ/kg mole °C)
F_R	Heat Removal Factor
A	area, (m^2)
I_b	beam radiation (W/m^2)
U	heat transfer coefficient (W/m^2 K)
H	specific enthalpy (kJ/kg), Convective heat transfer coefficient (W/m^2 K)
R_b	the beam radiation tilt factor
N	number of glass, Number of effects
R_a	entrainment ratio

Greek Letters

α	absorbance
η	efficiency
ω	acentric factor
Σ	sum
$\int$	integration
τ	transmittance
ε	emissivity
β	the tilted angle
B	bottom loss
U	useful

Superscript

T	thermal component
P	pressure component

Abbreviations

MED	multi effect desalination
NEA	non-equilibrium allowance
TVC	thermo vapor compressor
LMTD	logarithmic mean temperature difference
SF	solar fraction

Names Used for Blocks in Plants

C_i	compressor
E_i	evaporator
T_i	turbine
HX_i	multi stream heat exchanger
D_i	flash drum
V_i	valve

Subscripts

C	cold, collector
H	hot
I	inlet
O	outlet
Id	ideal
Ph	physical
Ch	chemical
T	total
W	water

geothermal energy [10,11]. Multi-stage flash desalination process is a commercialized thermal desalination. In this process, vapor is generated from seawater or brine [12]. The multi-stage desalination process performance is proportional to the number of stages [13]. Multi-stage systems are easy to manage and capable to work with very salty water up to 70,000 mg/l [14].

In 1980s Alexander I. Kalina [15] presented a new thermodynamical power generation cycle. This cycle used a binary fluid-mixture of water and ammonia- as a working fluid. Kalina cycle theoretically converts about 45% of input heat to electricity [16]. The most beneficial advantage of the Kalina cycle is that this cycle can generate electricity from low-temperature sources such as geothermal wells or low-temperature solar systems [17,18]. in comparison to the Organic Rankine cycles which is conventional in geothermal energy production, Kalina cycle generates 30–50% more power [19].

Several multi- production systems have been investigated so far. Here, some of the recent work which are mainly focused on combination of solar energy, desalination systems, and Kalina cycle are reviewed.

Ogriseck [20] investigated integration of the Kalina cycle in a combined heat and power plant in Bensheim, Germany. The results showed that Kalina cycle improves the plant efficiency. Lolos and Rogdakis [21] used solar flat collectors as a low-temperature heat source (70 °C) for the Kalina power cycle. Ashouri et al. [22] performed analysis on a driven Kalina cycle through a parabolic trough solar collector. It has been shown in Techno-economic investigation that solar collector and vapor generator are the most exergy destructive device of the considered system. Their economic investigation showed 0.1611 $/kW h higher levelized cost for the Kalina cycle than a fuel driven cycle. Hosseini et al. [23] investigated a combined power and multi-stage flash desalination plant and studied through thermo-economic analysis and reliability. It has been illustrated that considering reliability, increased the water and power cost by 4.1% and 6.4%, respectively. Sanaye and Asgari [24] studied combined cycle power plants integrated with a multi-stage flash desalination unit. The system was evaluated by considering 4 analysis fields: Energy, Exergy, Environmental and economic. It is reported that the ambient temperature variation affect the output power, distillate production, income, and payback period. Shaobo et al. [25] investigated performance optimization of a solar multi-stage flash desalination process by using pinch technology and analyzed the temperature difference fluctuation influence on different desalination stages. It is reported that temperature fluctuation in desalination stages' had a negative effect on the performance of the whole desalination unit. Alsehli et al. [26] proposed a solar desalination system with a dual thermal storage tank. Dual thermal storage tank minimizes the solar energy daily variation effect. Yari et al. [27] investigated coupling of a humidification-dehumidification desalination (HDD) with an organic rankine cycle (ORC) as a multi-generation system to produce power, distilled water, and heat. The presented multi-generation system was assessed thermodynamically and economically and demonstrated that with utilization n-Octane as a working fluid in the system, higher recovery rate, lower cost, and more distilled water were produced. Islam et al. [28] studied a solar based muti-generation system which is combined with a thermoelectric generators through energetic and exergetic viewpoints. Two different scenarios were considered: in the first model a thermoelectric generator was coupled with the parabolic solar collectors, and the second model was consist of an incorporation of a thermoelectric