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Performance investigation of a novel water–power cogeneration plant (WPCP) based on humidification dehumidification (HDH) method

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ABSTRACT

Humidification dehumidification (HDH) technology was well applied to produce freshwater in the desalination system. However, besides the demand of freshwater, power is also required simultaneously in most situations. In the paper, a novel water–power cogeneration plant (WPCP) based on the HDH desalination system coupled with the organic Rankine cycle (ORC) is proposed. Energy analysis for the proposed combined system at different appointed operation parameters is achieved, and the corresponding performance correlation between the HDH desalination and ORC power system are revealed. It is verified that the production of freshwater and electricity can be gained synchronously in the suggested novel platform, and the performance of the whole system is really sensitive to the operation parameters of the HDH desalination system. It is found that after the regulation of the operation pressure, p, and the seawater temperature at the outlet of the seawater heater, $T_{sw,2}$, for the HDH desalination from $p = 0.1$ MPa, $T_{sw,2} = 353.15$ K to $p = 0.3$ MPa, $T_{sw,2} = 383.15$ K, a maximum elevation, 25.46 kg h^{-1} for the freshwater production, 4.17 kW for the electricity and 2% for the extended gained output ratio (EGOR) is obtained. Furthermore, owing to the asynchronism between the specific production and the final energy utilization efficiency, the balance should be optimized among the demand of the freshwater and power and the efficiency of the novel WPCP.

1. Introduction

In virtue of the water resources shortage all over the world, more and more attentions were put on the desalination methods as well as the corresponding devices in the past decades. As a very important pattern of the desalination method, thermal desalination devices with different principles were put into reality continuously. However, such desalination methods, including multi-effect evaporator (MEE) [1], multi-stage flash (MSF) [2], thermal vapor compression (TVR) [3], mechanical vapor compression (MVC) [4], were only applicable for the large scale demand of freshwater supply. However, a huge amount of thermal energy was necessary to complete the freshwater production in the demonstrated desalination plants above, and the relevant small scale applications was limited owing to a low energy utilization efficiency. As a result, desalination devices for small scale demands of freshwater are also necessary for special occasions, such as the watercraft and island. Recently, a promising technology with a high efficiency called humidification dehumidification was extensively investigated by the ways both of numerical simulation and experiments [5–7].

Narayan [8] numerically investigated various HDH desalination thermal cycles by the platform of Engineering Equation Solver, and thus novel improvement measures were proposed to raise the relevant performance of the original desalination systems based on the obtained simulation results. It was also validated that the desalination systems with these novel cycles show more prominent capability.

Hamed [9] established a mathematical model to evaluate the performance as well as the productivity of a solar desalination unit based on HDH method. The produced freshwater from the proposed system was calculated, and the results told that the highest freshwater production arised from 13 pm to 17 pm in a day. In addition, a corresponding experimental platform was also established to measure the characteristics in the desalination system, and finally the theoretical results were validated through the experimental data. The performance of water and air heated solar powered HDH desalination system for various operating and

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Nomenclature

c_p	specific heat (J kg^{-1} K^{-1})
h	specific enthalpy (kJ kg^{-1})
m	mass flow rate (kg s^{-1})
p	pressure (MPa); wet perimeter (m)
Q	heat load (kW)
S	concentration of seawater (g kg^{-1})
T	temperature (K)
v	velocity (ms^{-1})
w_1	humidity ratio at the inlet of the humidifier (kg kg^{-1})
w_2	humidity ratio at the outlet of the humidifier (kg kg^{-1})
W	power (kW)

Greek letters

ρ	density (kg m^{-3})
μ	dynamic viscosity(kg m^{-1} s^{-1})
ε	effectiveness of the humidifier and dehumidifier
ϕ	relative humidity
γ	latent heat (kJ kg^{-1})

Subscripts

a	air
b	brine
c	condenser
d	dehumidifier
da	dry air
ev	evaporator
h	hot; humidifier
i	initial
im	intermediate
m	maximum
o	outlet
ORC	organic Rankine cycle
p	pump
pin	pinch
pw	pure water
r	reheat
s	saturation
sw	seawater
t	total; turbine
w	water

design parameters under climatological conditions of Antalya, Turkey was studied by Yildirm [10], and the relevant mathematical model was established and the corresponding governing conservation equations were numerically solved. A parabolic trough solar collector (PTSC) was advised to be integrated into the open air, open water, air heated HDH system by Al-Sulaiman [11], and the corresponding thermodynamic performance was analyzed. The influences from the configurations of the solar air heater on the performance of the whole HDH desalination system were discussed. It was revealed that PTSCs were well suited for air heated HDH systems for high radiation locations, and the HDH configuration with the air heater placed between the humidifier and the dehumidifier has a better performance and a higher productivity. He [12] achieved a numerical investigation based on the platform of a water heated closed air open water (CAOW) HDH desalination system powered by waste heat. It was found that modified heat capacity ratio of the dehumidifier was critical for the performance of such HDH desalination system as well as the plate heat exchangers, and a top value of gain output ratio, GOR = 2.44, was obtained at the balance point of the dehumidifier at the raised pressure of p = 0.15 MPa. Furthermore, gain investment ratio was also advised to describe the overall investment of the whole system.

From the desalination systems in the previous literatures, only the production of freshwater was provided. Nevertheless, the demand of freshwater and electricity were always existing synchronously for most occasions, and the water–power cogeneration plant were also proposed and investigated [13–15]. Kotb [16] proposed a MSF desalination model in proximity of a 650 MW power plant to provide 385.03 kg/s superheated steam from low pressure part of heat recovery steam generator. It was found that a gained output ratio of 8.76 for the desalination system can be achieved with 28 flashing stages, and the freshwater production can reach 2229 kg/s. The obtained results showed the expected performance of the designed MSF desalination were determined. Furthermore, owing to the existing waste heat, the integration of the desalination system and the waste heat recovery technology is another way to supply the freshwater and electricity. Al-Weshahi [17] attempted to recover the heat stored in the MSF desalination distillate water with an organic Rankine cycle [18,19], which used the organic fluid with low boiling temperature as the working medium [20,21]. It was found that a highest net power of the ORC system, 359 kW for R245fa and 307 kW for R134a will attain with extraction up to MSF stage 8. The obtained results also presented that the influence of variation of the evaporator and cooling temperature on ORC performance was significant for both refrigerants.

The literature survey showed that the thermal system with simultaneous freshwater and electricity supply was feasible, while the existing proposed systems were based on large scale desalination method, such as MSF. However, according to the characteristics of the HDH desalination system, Mehrgoo [22] showed it was a waste of energy if the hot emission concentrated seawater was discharged into ambient directly. As a result, the waste heat of the emission seawater can be utilized to generate power with a power system, and such related investigations were never involved. In the paper, a novel water–power cogeneration plant (WPCP), in which the hot concentrated seawater from the humidifier is reheated and then produces electricity with the platform of organic Rankine cycle, is proposed. Energy analysis at different appointed operation parameters of the desalination subsystem for the combined system is achieved and compared, and the corresponding performance correlation between the HDH desalination and ORC power subsystems are simulated and analyzed. The research results provide significant references for the design and farther optimization for the water–power cogeneration plants.

2. Description of the water–power cogeneration plant

The schematic of the water–power cogeneration plant based on humidification dehumidification method is presented in Fig. 1. It is found that there are two thermal cycles within the combined system, containing the HDH desalination thermal cycle and the ORC. Evidently, the driven force of the HDH desalination cycle comes from the heat transferred to the seawater in the heater. The seawater with the top temperature enters the humidifier, and mass and heat transfer arises between the hot seawater and the humid air from the dehumidifier. After the humidification process, the concentrated seawater flows out at the bottom of the humidifier. The concentrated seawater is reheated to the top temperature in