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Performance simulation of a power-water combined plant driven by low grade waste heat

W.F. He [a,*], W.P. Zhu [b], D. Han [a], L. Huang [a], Y.K. Wu [a], X.K. Zhang [a]

[a] Nanjing University of Aeronautics and Astronautics, College of Energy and Power Engineering, Nanjing 210016, China
[b] State Grid Jiangsu Electric Power Company Research Institute, Nanjing 211103, China

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ABSTRACT

Both power and freshwater are obligatory for life and industry production. The present paper suggested a novel power-water combined plant (PWCP) driven by low grade waste heat to supply power and water simultaneously, in which the organic Rankine cycle (ORC) and air-heated humidification dehumidification (HDH) desalination subsystem are coupled. Through the connection effect of the condenser for the ORC power subsystem, mathematical models of the combined plant are presented. The relevant performance of the combined plant at the designed conditions is simulated iteratively, and the influences from the condensing temperature and pinch temperature difference (PTD) are investigated. The simulated results show that the peak value of the output power arrives at W_{net} = 14.90 kW when the evaporation temperature of R123 is T_1 = 401.15 K. Based on the conditions at the maximum power case of the ORC, the maximum freshwater production reaches m_{fw} = 381.66 kg h^{-1} at the balance condition of the dehumidifier, HCR_d = 1 at m_{sw} = 2.9 kg s^{-1}. Accordingly, the peak value of the gained output ratio (GOR), GOR = 1.93, also indicates the best energy utilization situation within the HDH desalination system at HCR_d = 1. After the regulation of the condensing temperature as well as pinch temperature difference of the ORC subsystem, a peak value of power for the ORC system, W_{net} = 16.56 kW at T_3 = 338.15 K, and maximum value of the freshwater production, m_{fw} = 381.66 kg h^{-1} at T_3 = 343.15 K are obtained.

1. Introduction

Due to the shortage of the fossil fuel, such as coal, petroleum and natural gas, the concept of energy conservation have been paid more and more attentions. As one of the main energy form, electricity is always requisite both for life and industry production in spite of a great energy consumption and environment pollution. Accordingly, how to reduce the energy expenditure and related pollution is an urgent problem to be solved. Organic Rankine cycle, which is applicable to utilize low grade waste heat or renewable energy, is extensively investigated through both theory and experiment methods in the past ten years [1–3], and it is especially significant for China, which has the greatest population and commercial scale.

Chen [4] took the configuration of solar chimney to utilize the waste energy. In the solar chimney, low temperature waste heat was first applied to create an air updraft, which can propelled a turbine installed at the chimney tower base converting the waste heat into power. A better stability of air velocity than that of the air flow rate and the relevant pressure difference was found once the temperature of heat source and ambient air or heat transfer area varied. Zerotropic mixtures were considered into the ORC layout by Sadeghi [5] for an improved overall performance. According to the presented thermodynamic and optimization analysis, compared to the pure fluid, an raised amplitudes of 27.76%, 24.98% and 24.79% were found respectively in the simple, parallel two-stage and series two-stage ORC systems once zerotropic mixtures were applied as the working fluid. In addition, the application of the zerotropic mixtures will contribute a reduced scale of the turbine, which also indicated a decreased final investment. Kang [6] investigated an ORC with a two-stage radial turbine, which has a higher pressure ratio. The detailed design process of the whole thermal cycle and the forementioned two-stage radial turbine was completely exhibited, and the corresponding performance was investigated experimentally. Different from the most existing literature using radial turbine, Lio [7] proposed a design criterion for the axial flow expanders in the ORC, and the efficiency estimation procedures for a wide range of working fluids and operating duty were presented, with the influences from the design features taken into account. Wang [8] executed the thermodynamic and

* Corresponding author at: Nanjing University of Aeronautics and Astronautics, No. 29 Yudao Street, Qinhuai District, Nanjing, Jiangsu Province 210016, China.
E-mail addresses: wfhe@nuaa.edu.cn, heweifeng_turbine@163.com (W.F. He).

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Nomenclature

Roman symbols
- c_p specific heat (J kg^{-1} K^{-1})
- d humidity ratio (g kg^{-1})
- h specific enthalpy (kJ kg^{-1})
- h_{fg} latent heat (kJ kg^{-1})
- H total enthalpy (kW)
- m mass flow rate (kg s^{-1})
- p pressure (MPa)
- Q heat load (kW)
- S concentration of seawater (g kg^{-1})
- T temperature (K)
- W power (kW)

Greek letters
- ε effectiveness
- ϕ relative humidity

Subscripts
- *a* air
- *b* brine
- *c* condenser
- *d* dehumidifier
- *da* dry air
- *e* evaporator
- *fw* freshwater
- *h* hot; humidifier
- *ha* humid air
- *i* initial
- *m* maximum
- *ORC* organic Rankine cycle
- *p* pump
- *pin* pinch
- *s* saturation
- *sw* seawater
- *t* total; turbine
- *w* water
- *we* waste heat

optimization analysis within an ORC using low grade heat source. The effects from critical thermodynamic parameters, such as pressure and temperature at the turbine inlet, pinch and approach temperature difference in the heat recovery equipments, on the net output and surface areas using R123, R245fa and isobutane were validated. Furthermore, it was revealed that the isobutane used ORC system has the most prominent performance compared to that with R123 or R245fa.

In addition of the electricity, freshwater is also an integrant component for life and industrial production while the problem due to freshwater shortage is more and more serious. Therefore, desalination systems, especially the thermal version [9–11], were proposed gradually to solve the forementioned water crisis. In the light of the great significance both of water and electricity, it is reasonable to couple the ORC power and desalination subsystem to provide water and electricity coinstantaneously. Nevertheless, general thermal desalination cycle were always integrated with the large power plant to obtain the scale effect. As a result, a small scale desalination method with high efficiency is more and more requisite. Fortunately, the HDH desalination system was advised and developed due to the efficient energy utilization within the thermal cycle [12,13].

Another experimental study with a dual solar collector, which was used to heat the water and air, considered in a humidification dehumidification desalination system was also reported by Rajaseenivasan [14]. In the desalination system, the hot water and air from the solar collector flows into the humidifier. The experimental results showed that the distillation capacity was related to the mass flow rate of air, hot water and cold water as well as the air and water temperature. The highest productivity arrived at 12.36, 14.14 and 15.23 kg/m^2 day for the without turbulators, convex and concave turbulators respectively, and an overall efficiency of 67.6% with the concave turbulators was also found in the investigated system. To raise the water production under the fixed input power, Muthusamy [15] proposed a modified HDH system through significant changes at the core internal components. Two types of packing materials were applied in the humidifier, and two different dehumidifier were tested to choose the better one. The best configuration was identified through the investigations among all the schemes. The investigation results showed that a higher water production of 0.8 kg/h was attained with 40% saving of the input power within the modified HDH desalination system. Solar evacuated tubes was integrated into a humidification-dehu midification desalination system by Zubair [16], and the relevant performance was optimized. Then the optimal desalination system was operated in different locations, and the freshwater production and expense were also determined. The influences from the effectiveness of the humidifier and the dehumidifier and the number of collectors were studied. To reach a comprehensive study of the proposed system, a cost analysis was also performed to determine the feasibility of the system and the cost of water production.

Actually, the combined system uniting the ORC and desalination system is not innovative. In order to recover the released heat from a desalination system, ORC was always regarded as the bottom cycle to produce power. For example, the ORC system was utilized to recycle the carried heat by the distillate water produced in the desalination system [17]. It was found that seen that a maximum output power of 359 kW for R245fa and 307 kW for R134a can be obtained when the extraction of the multi-stage flashing system was up to stage 8. Furthermore, the related impacts resulting from the evaporation and cooling temperature on the performance of the ORC system was also validated for all the involved refrigerants. At the aspect of the coupled system with the HDH desalination system and ORC system, a new water-power cogeneration plant, in which organic Rankine cycle was used to recover the heat of the concentrated seawater was proposed [18]. Performance analysis of the combined plant based on the mass and energy equilibrium was implemented. The simulation results showed that elevation of the pressure and top temperature within the desalination system was significant to raise the final production, including freshwater from the HDH desalination system and power from the ORC.

Therefore, in view of the literature survey, it was discovered that considering the ORC power system as the top cycle to drive the HDH desalination system by the condensing latent heat is innovative, especially with the air-heated HDH desalination as the bottom thermal cycle. As a result, both electricity and freshwater can be supplied. In this paper, the organic Rankine cycle (ORC) driven by low grade waste heat and air-heated humidification dehumidification (HDH) desalination subsystem are coupled to