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Thermodynamic analysis of siphon flash evaporation desalination system using ocean thermal energy

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ABSTRACT

Ocean thermal energy refers to the thermal potential energy produced by the temperature difference between the warm surface seawater and the cold deep seawater. In this paper, a siphon flash evaporation desalination system using ocean thermal energy is proposed. Because it can utilize the ocean thermal energy directly for desalination, siphon flash evaporation desalination system has relatively higher energy efficiency compared with converting ocean thermal energy into electric energy and then using electric energy for desalination. The working principle of this system is introduced firstly. Then, the exergy, exergy loss and exergy efficiency in the flash evaporation, condensation and the whole system are carried out quantitatively. The results show that the exergy efficiency of the system which directly utilizing ocean thermal energy for desalination reaches to 7.81% under design conditions; lower surface seawater temperature, higher deep seawater temperature and higher flash temperature can result in an increasing of system efficiency, while the whole energy consumption shall also be taken into consideration. Then the simulation model of the whole system is created in ASPEN PLUS in order to investigate the influence of some most important parameters, such as surface seawater temperatures, deep seawater temperatures and difference of inlet temperature between surface and deep seawater. Finally, an experimental platform is established based on the working principle and process to verify the validity of the working principle and the simulation model. The siphon flash evaporation desalination system provides a novel method of direct high efficient conversion and utilization of ocean thermal energy and this work can provide the theoretical support for the feasibility of similar engineering applications.

1. Introduction

Ocean thermal energy (OTE) refers to the thermal potential energy produced by the temperature difference between the warm surface seawater and the cold deep seawater. Due to the huge ocean area, the total reserves of OTE are enormous. Meanwhile, OTE is a kind of renewable energy without any pollution. However, there are two main weaknesses of OTE. One is its low temperature difference between surface and deep seawater, ranging from 15 K to 25 K generally. The other is its low specific heat, which is about 4 J/(g K), while the heat of vaporization of seawater is about 2400 J/g.

Many research works have been done on the topic of converting the OTE into other kinds of energy. Soto et al. utilized OTE to enhance the efficiency of thermal power plant and the thermal efficiency of the proposed system reached 3.4% and its thermal power plant net efficiency could also increase by 1.3% [1]. At the same period, the method of combining OTE with solar energy had been used in ocean thermal energy conversion system. Aydin et al. designed an OTE conversion system with closed-cycle and figured out that a solar preheater and a super heater could both enhance the net power generation [2]. Meanwhile, Ahmadi et al. designed also developed a new multi-generation system with an OTE and PV/T solar collectors, and an economic assessment was also presented [3]. Ahmadi et al. investigated a hydrogen production system by using OTE conversion, and a parametric study for improving the energetic and environmental performances showed that the energy and exergy efficiencies of the integrated OTEC system can reach 3.6% and 22.7% [4]. For desalination technology, there are also many interesting research works. Muthunayagam et al. demonstrated theoretically and experimentally the feasibility

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Nomenclature

ΔA	total exergy losses of the whole system, kW
ΔA_c	total exergy losses of condenser, kW
ΔA_{ch}	exergy loss caused by non-isothermal heat transfer in condenser, kW
ΔA_{cp}	exergy loss caused by pressure drop in condenser, kW
ΔA_f	total exergy losses in flash evaporator, kW
ΔA_{fd}	exergy losses caused by desalinated seawater diffusion, kW
ΔA_{fh}	total heat exergy losses in flash evaporator, kW
ΔA_{fhv}	heat exergy losses by vaporized seawater, kW
ΔA_{fhw}	heat exergy losses by cooling seawater, kW
ΔA_{fp}	exergy losses caused by pressure drop in flash evaporator, kW
CIW	inlet flow of deep seawater
COW	outlet flow of deep seawater
C_w	specific heat capacity of seawater, kJ/kg K
C_d	specific heat of deep seawater, kJ/kg K
C_s	specific heat of surface seawater, kJ/kg K
E_{ci}	exergy entering condenser, kW
E_{co}	exergy flowing out of condenser, kW
E_f	total exergy entering in flash evaporator, kW
E_{fwi}	exergy of surface seawater entering the flash evaporator, kW
E_{fwo}	exergy of desalinated seawater expelled from the evaporator, kW
E_{fv}	exergy of vapor
E_{in}	exergy entering the whole system
E_{out}	exergy expelled from the system
h_{d1}	enthalpy of inlet deep seawater, kJ/kg
h_{d2}	enthalpy of outlet deep seawater, kJ/kg
h_f	enthalpy of fresh seawater, kJ/kg
HIW	inlet flow of surface seawater
h_0	enthalpy of seawater under ambient temperature, kJ/kg
HOW	outlet flow of surface seawater
h_{s1}	enthalpy of inlet surface seawater, kJ/kg
h_{s2}	enthalpy of outlet surface seawater, kJ/kg
h_v	enthalpy of vapor, kJ/kg
m_{d1}	mass flow of inlet deep seawater, kg/s
m_{s1}	mass flow of inlet surface seawater, kg/s
m_{s2}	mass flow of outlet surface seawater, kg/s
M_w	molar mass of water, kg/k mol
OTE	ocean thermal energy
ΔP_d	pressure drop of deep seawater in condenser, kPa
P_{d1}	pressure of inlet deep seawater, kPa
P_{d2}	pressure of outlet deep seawater, kPa
P_f	pressure of outlet fresh water, kPa
P_{s1}	pressure of inlet surface seawater, kPa
P_{s2}	pressure of outlet surface seawater, kPa
P_v	pressure of vapor, kPa
Q	quantity of heat, kW
R	universal gas constant, kJ/kg K
SFEDS	siphon flash evaporation desalination system
s_{d1}	entropy of inlet deep seawater, kJ/kg K
s_{d2}	entropy of outlet deep seawater, kJ/kg K
s_f	entropy of fresh seawater, kJ/kg K
ΔS_{fhw}	entropy increase of cooling seawater, kJ/kg K
ΔS_{fhv}	entropy increase of vaporized seawater, kJ/kg K
S_0	entropy of seawater under ambient temperature, kJ/kg K
s_{s1}	entropy of inlet surface seawater, kJ/kg K
s_{s2}	entropy of outlet surface seawater, kJ/kg K
s_v	entropy of vapor, kJ/kg K
ΔT	temperature difference of flash temperature, K
ΔT_d	temperature change of deep seawater, K
ΔT_s	temperature change of surface seawater, K
ΔT_{sd}	difference of inlet temperature between surface and deep seawater, K
T_{d1}	temperature of inlet deep seawater, K
T_{d2}	temperature of outlet deep seawater, K
T_0	environmental temperature, K
T_f	temperature of freshwater, K
T_v	flash temperature, K
T_{s1}	temperature of inlet surface seawater, K
T_{s2}	temperature of outlet surface seawater, K
T_v	temperature of vapor, K
v_{d1}	volume flow of deep seawater, m^3/s
VIN	vapor flow
WOUT	outlet flow of freshwater
x_{s1}	solute molar concentration of inlet surface seawater, kg/k mol
x_{s10}	solvent molar concentration of inlet surface seawater, kg/k mol
x_{s2}	solute molar concentration of outlet surface seawater, kg/k mol
x_{s20}	solvent molar concentration of outlet surface seawater, kg/k mol
η	exergy efficiency of the system
η_c	exergy efficiency of condenser
η_f	exergy efficiency of flash evaporator

of OTE desalination through the droplet flash evaporation model and their experimental devices with seawater at temperatures between 309 K and 315 K [5] and it could reach 0.1 MPa of water injection pressures [6]. Kumar et al. also used vacuum desalination system and obtained the detailed data [7], indicating that the freshwater production decreased when the evaporator pressure and the condensing temperature increased, while it only increased when the evaporation temperature increased [8]. Methods of using solar energy for desalination had been given by Al-Kharabsheh et al. and Gude. In Al-Kharabsheh et al. work, a theoretical analysis was carried out [9], and in Gude also analyzed the possibility using low grade heat sources for desalination [10]. In these methods, the seawater was heated by solar to a temperature above 323.15 K. A multiple effect distillation system had been proposed by Aly S E and it showed that the evaporation range was extended to 279.15–336.15 K [11]. Other systems which utilized solar energy for desalination also were proposed. Mahkamov et al. mainly developed a fluid piston converter for a small solar thermal desalination plant [12], while El-Agouz et al. mainly analyzed the performance evaluation of the proposed desalination system [13]. Furthermore, Elminshawy et al. developed the desalination system not only using solar energy, but also using low grade waste heat [14]. Because these systems utilizing solar energy, the required amount of seawater is smaller than the systems utilizing OTE only, Li et al. paid attention to reversing the electrodialysis and osmosis for seawater desalination by a novel hybrid process [15]. Meanwhile, Zhao et al. also combined forward osmosis and membrane distillation together for desalination [16], and Altaee et al. analyzed the performance of the pressure retarded osmosis for seawater desalination and power generation [17]. At the same time, Guo et al. [18] and Figoli et al. [19] both developed novel functionalized carbon quantum dots and hollow fibers for seawater desalination.