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Performance analysis of an absorption power cycle for ocean thermal energy conversion

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ABSTRACT

An absorption power cycle with two ejectors is proposed for ocean thermal energy conversion. The ammonia–water is used as the working fluid. The ejectors are driven by vapor and solution from the sub-generator. Based on the first and second law, the mathematical model for this cycle is developed and theoretical analysis is conducted to evaluate the effects of thermodynamic parameters on the performance of this cycle. Results show that the absorption temperature is increased by 2.0–6.5 °C by employing the two-stage ejector sub-cycle, which indicates that this proposed cycle can be driven with a lower temperature difference. Further, the thermal efficiency, net thermal efficiency and exergy efficiency of this cycle can reach to 4.17%, 3.10% and 39.92% respectively. Besides, the generation pressure, the heating source temperature, the solution concentration, and the expansion ratio, as well as the entrainment ratio of the first stage ejector have significant effects on the absorption temperature, the thermal efficiency, the exergy efficiency and the exergy loss of this cycle. In addition, 49.80% of exergy loss in this proposed cycle occurs in the generators and reheater, followed by the ejectors of 36.12%.

1. Introduction

Ocean thermal energy is a kind of solar energy absorbed and stored in the upper layer of the ocean. It is exploited by means of ocean thermal energy conversion (OTEC) cycle. Such cycle utilize the top layer seawater (30–32 °C) as the heating source and deep seawater at a depth of 1000 m (4–6 °C) as the cooling source to drive a heat engine cycle and generate power [1]. Due to the relatively small temperature difference between heating and cooling source, the Carnot cycle efficiency for an OTEC cycle is limited at 8% [2]. However, the vast ocean thermal energy reserves still make it a promising research topic.

Generally, an OTEC cycle can take the form of either open-cycle or closed-cycle process. The open-cycle employs warm sea water as working fluid. Steam is evaporated in a flash evaporator and then drives a turbine to produce power. Then the steam is condensed and fresh water is obtained as a by-product. The closed-cycle operates similar to the open-cycle except that a refrigerating fluid is used as the working fluid. The refrigerant is evaporated by warm sea water in the generator and expands in the turbine to generate power [3].

Compared with the open-cycle, the closed-cycle has a higher thermal efficiency with the same temperature difference of sea water. This is due to the use of vacuum equipment in the open-cycle. On one hand, the entire open-cycle, from flash evaporator to condenser, operates under a partial vacuum condition. On the other hand, the non-condensable gas in sea water needs to be removed. Thus a vacuum compressor is used in the open-cycle and this increases extra power consumption [4].

But the closed-cycle's application in the OTEC cycle is far from satisfactory. For this reason, current research is mainly focused on the approaches of improving thermal efficiency.

One way to improve the performance of the closed-cycle consists in choosing a proper working fluid. Both the pure working fluid (i.e. R134a, R245a, and R601, etc.) and the binary mixture (i.e. ammonia–water mixture) can be used as the working fluid [5]. The binary mixture was found to be more appropriate and efficient for using in OTEC cycle, enable to reduce the heat transfer related irreversibility in evaporator and condenser [6–8]. This is because at a given pressure, the evaporation or condensation of a binary mixture occurs over range of temperatures, results in a lower temperature difference between the heating/cooling source and the working fluid. DiPippo [9] conducted a comparison of different working fluids in a closed-cycle. Results showed that the ammonia–water based cycle performs better with a low temperature of heating source (120 °C) and the theoretical thermal

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Nomenclature

Symbols

m	mass flow rate, kg s^{-1}
h	specific enthalpy, kJ kg^{-1}
E	exergy, kJ
I	exergy loss, kJ
T	temperature, °C
P	pressure, MPa
X	solution concentration, kg kg^{-1}
Q	heat input, kJ
W	turbine output, kJ
u	velocity, m s^{-1}

Subscripts

I, II	apparatus number
i = 1, 2...	state points
0	reference state
G	generator
T	turbine
R	reheater
A	absorber
SP	solution pump
WP	warm seawater pump
CP	cold seawater pump
WS	warm seawater
EJ	ejector
net	net
pf	primary flow
sf	secondary flow
d	diffuser
n	nozzle
m	mixing chamber
s	solution mixture
s'	isentropic process
$n1$	nozzle inlet
$n2$	nozzle outlet
in	input
out	output
$ratio$	ratio of two generators

Greek symbols

μ	entrainment ratio
β	expansion ratio
η	thermal efficiency, %
v	specific volume, m^3 kg^{-1}

Acronyms

OTEC	ocean thermal energy conversion
ex	exergy

efficiency is 3% higher than that of a pure working fluid based cycle.

Another way to make the improvement is to investigate new thermodynamic cycles. Great efforts were made to develop a novel binary mixture based cycle and a representative one is the Kalina cycle developed by Kalina [10]. The Kalina cycle, which employs the ammonia–water as the working fluid, was first designed to serve as a bottoming cycle for a combined-cycle energy system as well as for generating electricity using low-temperature heat sources. It proved to be an efficient power cycle and to have a higher thermal efficiency than a conventional Rankine cycle by about 10–20% [11]. Furthermore, researchers have proposed a Kalina cycle family and they carried out a number of theoretical studies to demonstrate these cycles' performance [12–23]. "Uehara cycle", proposed by Uehara and Ikegami [24], is a "modified" Kalina cycle. In this cycle, a part of the vapor is extracted in the turbine and fed through the heater and absorbed by the liquid in the absorber. This extraction process was added to improve thermal efficiency. Furthermore, Uehara et al. [25] presented numerical simulation for the Uehara cycle, and results showed that the thermal efficiency rises when the extraction mass fraction ratio increases. The concept of using an ejector in an ammonia–water based closed-cycle has been proposed recently. Yuan et al. [26] and Xinguo Li et al. [27] put forward novel types of one-stage ejector power cycle for OTEC separately. These one-stage ejector power cycles have showed a higher thermal efficiency than traditional ones. The ejector can lead to depressurization in the turbine outlet which has significantly improved the thermal efficiency by increasing the turbine power output.

However, little attention has been paid to approaches of increasing the cooling source seawater temperature for the OTEC cycle. It is interesting to note that the cooling source seawater temperature is closely related to its depth. When the seawater depth decreases from 1000 m to 200 m, its temperature draws a rapid increase [28]. This phenomenon provides a potential of broadening the scope of the OTEC cycle application: once a shallower depth of cooling source seawater can be used, both the energy consumption in the cold water pump and the cost of the expensive cold-water pipe that is used to pump seawater can be reduced.

In this study, an absorption power cycle with ejectors is proposed. The main objective of this study is to increase the absorption temperature for the OTEC cycle, which ultimately reduces the energy consumption in cold water pump by utilizing shallower depth of seawater as the cooling source. The absorption power cycle is thermodynamically modelled and assessed with energy and exergy analyses with a theoretical comparison with the performance of the one-stage ejector power cycle proposed in Ref. [26], including the evaluation of the effects of two-stage ejector subcycle on the absorption temperature and operation parameters.

2. Cycle description

The proposed absorption power cycle consists of two generators, two separators, two-stage turbines, two ejectors, two heat exchangers, a reheater, an absorber and a solution pump. This power cycle employs ammonia water as the working fluid and seawater as the heating/cooling source.

A two-stage ejector sub-cycle, which is shown in Fig. 1, consists of a sub-generator, a heat exchanger and two ejectors, is employed to get a higher absorption temperature in the absorber. A reheater is introduced between the turbines to improve the thermal efficiency. The generator I performs as the primary generator, providing ammonia vapor (state point 3) which drives the turbines to produce power. The generator II performs as the sub-generator, in which ammonia vapor (state point 7) is generated as the primary fluid of the ejector I. The turbine exhaust vapor (state point 6) is first ejected as the secondary fluid of the ejector I and then mixes with the ammonia vapor generated from the generator II before flowing into the ejector II as the secondary fluid (state point 8). Simultaneously, the weak solutions discharged from the generators (state point 2, 17) mix together (state point 9) and enter the ejector II as the primary fluid. The weak solution (state point 9) and the ammonia vapor (state point 8) are preliminarily mixed in the ejector II and then flow into the absorber to produce the strong