Renewable Energy 132 (2019) 1018–1033

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Techno-economic analysis of closed OTEC cycles for power generation☆

C. Bernardoni, M. Binotti*, A. Giostri

Politecnico di Milano, Dipartimento di Energia, Via Lambruschini 4, 20156 Milano, Italy

ARTICLE INFO

Article history:
Received 18 December 2017
Received in revised form
6 July 2018
Accepted 2 August 2018
Available online 3 August 2018

Keywords:
Renewable energy
Ocean thermal energy conversion
OTEC
Plate heat exchanger
Ammonia cycle

ABSTRACT

This study aims at offering a techno-economic evaluation of closed OTEC cycles for on-shore installations. A flexible Matlab® suite has been developed to identify plant design parameters (temperature difference of cold and warm seawater, pinch-point temperature difference of evaporator and condenser etc.) that guarantee the maximum value of γ (ratio between electricity output and heat exchangers area). The optimization model is able to handle different working fluids through the addition of specific correlations that consider fluid influence on heat transfer coefficients and turbine performance. Each plant component is technically analyzed and, in particular, plate heat exchangers were considered for evaporator and condenser and sized accurately with Aspen EDR®, while expander was analyzed with the in-house code Axtur. For warm seawater temperature of 28 °C and cold seawater temperature of 4 °C (8500 kg/s taken from 1000 m depth), ammonia cycle is the best solution characterized by efficiency equal to 2.2% and net power output equal to 2.35 MW_e.

The obtained LCOE (269 €/MWh_e) confirms how OTEC technology is not ready to compete in energy market. Nevertheless, remote zones (i.e. small islands archipelagos), which are often characterized by high electricity price, represent interesting scenarios where OTEC technology could be a promising alternative to conventional power production technologies.

1. Introduction

Due to the increase in global electric energy demand [1] and the stipulation of new international climate agreement [2], renewable energy sources such as Ocean Thermal Energy Conversion ("OTEC") are acquiring larger interest. OTEC plants use the temperature difference between warm shallow water of tropical oceans and deep cold water to produce electric energy. Since temperature differences between warm and cold seawater in tropical oceans is generally between 22 °C and 26 °C [3] the maximum theoretical efficiency obtainable with an ideal Carnot cycle operating among these temperatures is about 5–6%.

Two main configurations have been proposed for OTEC: the open cycle and the closed cycle plant [4]. In the open cycle (OC-OTEC) plant, warm seawater enters a flash evaporator, it is expanded in a turbine and condensed by cold seawater. In the closed cycle solution (CC-OTEC), which is directly considered in this study, a working fluid with favorable features is used generally in a saturated vapor Rankine cycle: warm seawater evaporates the working fluid and cold seawater condense working fluid after expansion in the turbine. In the CC-OTEC the most diffused working fluid is undoubtedly ammonia [3].

In both the OC-OTEC and CC-OTEC a large pipe is required to collect cold seawater from the depth of the oceans. The cold water pipe (CWP), is a critical component of OTEC plants because it can reach an average depth of 1000 m [5] depending on the seawater temperature-depth profile of the selected site; CWP diameter and thickness are constrained by stresses related to pipe weight, currents, tides, waves and storms [3]. The larger the CWP diameter is, the larger the cold seawater flowrate and thus the thermal power leaving the plant can be. Therefore, cold water pipe diameter is proportional to OTEC plant size. In the OC solution, large turbines are required because of large specific volume of low pressure seawater vapor flowing in the turbine: concerns on mechanical resistance of the turbine exist [3]. The opportunity to select the working fluid in the thermodynamic cycle in order to limit components dimensions, is the main advantage of the closed solution,

☆ Web-site: www.gecos.polimi.it.

* Corresponding author.
E-mail address: marco.binotti@polimi.it (M. Binotti).

https://doi.org/10.1016/j.renene.2018.08.007
0960-1481/© 2018 Published by Elsevier Ltd.

Acronyms

CC	Closed Cycle
CWP	Cold Water Pipe
HDPE	High density polyethylene
HX	Heat Exchanger
OC	Open Cycle
OTEC	Ocean Thermal Energy Conversion
PHX	Plate heat exchanger
RFP	Reinforced plastic

Nomenclature

A	Area m^2
C	Specific heat J kg^{-1} K^{-1}
d	Depth m
D	Diameter m
F	Fanning friction factor
G	Mass flux kg m^{-2} s^{-1}
H	Heat transfer coefficient W m^{-2} K^{-1}
K	Thermal Conductivity W m^{-1} K^{-1}
M	Molecular mass kg $kmol^{-1}$
$\dot{m}$	Mass flow kg s^{-1}
P	Pressure Pa
Pr	Prandtl number
Q	Thermal power kW
R	Thermal resistance m^2 K^1 W^{-1}
Re	Reynolds number
SP	Size parameter m
T	Temperature K
U	Global heat transfer coefficient W m^{-2} K^{-1}
v	Velocity m s^{-1}
w	Specific work kJ kg^{-1}
W	Power kW

Greek letters

Δ	Difference,
γ	Gamma parameter, kW_e m^{-2}
η	Efficiency,
τ	Time, s
ψ	Ratio between convective heat Transfer coefficient,

Subscripts

c	Cold
cond	Condenser
eva	Evaporator
l	Liquid
ml	Mean logarithmic
pp	Pinch point
sw	Seawater
w	Warm
wf	Working fluid

which has been the most studied plant configuration so far [5]. However, the main disadvantage of the closed cycle solution is that large heat transfer areas are required and since heat exchangers operate in a chemically aggressive environment (seawater), expensive materials such as titanium are required. It has been assessed that heat exchangers cost in the closed cycle solution is 25–50% of total plant investment cost [6].

The OTEC concept was proposed for the first time in 1881 by French physicist D'Arsonval. Technical feasibility was demonstrated by Claude in 1928 with a demonstration plant in Belgium which used water at 30 °C from a steel plant as warm source and water from the river Meuse as thermal sink. Claude attempted many times to apply the OTEC concept in large scale plants, but all his projects, apart from a 50 kW which operated for 11 days, failed. The research and commercial development of OTEC was abandoned until the late seventies, when a rise in oil prices pushed US to start an OTEC development program. In 1979, the demonstrative Mini-OTEC closed cycle plant operated for three months on a ship with ammonia as working fluid. Further developments demonstrated technical feasibility in attaching a 670 m cold water pipe and a 1370 m mooring system [3]. Anyway, OTEC development in the 80s and 90s was abandoned by US government. Saga University in Japan in 1981 constructed an onshore demonstration CC plant on the Coast of Nauru Island. The plant operated with R22 as working fluid and produced 100 kW_e gross power for three months [7]. Apart from these successful experiences, no other pilot plant has been developed in the rest of the 80s and 90s because of lack of funding. In recent years, because of an increase in environmental issues and the opportunity to reduce fossil fuels consumption, ocean thermal energy conversion gained new attention. In 2013, a 100 kW_e net power CC OTEC plant started operation in Kumejima island, Japan [8]. The plant is still in operation. Finally, in 2015 Makai celebrated completion of a 100 kW_e plant in Hawaii connected to the electric grid. Many other projects are currently under development throughout the world.

Although technical feasibility has been demonstrated by several pilot plants installed throughout the years [9], CC-OTEC economic feasibility still requires to be demonstrated because of high heat exchangers cost and uncertainties related to CWP, which determined failure of many projects in the past [10].

This paper is focused on CC-OTEC, discussing both thermodynamic and technical aspects. Thermodynamic bases of CC-OTEC are discussed in order to identify the operating context. A tailored-made model, whose characteristics are discussed in the following sections, was developed in Matlab® in order to investigate CC-OTEC based on saturated Rankine cycle and the model flexibility was exploited in order to study the influence of working fluid choice.

Because of the well-known strong impact on OTEC systems performance of heat exchangers (HX), a detailed analysis of these components is performed in order to increase the level of accuracy of the modelling approach. Plate heat exchangers (PHX) are selected, being recognized as the most favorable solution for OTEC systems. An optimization tool, exploiting the capabilities of the cycle thermodynamic model, is developed with the aim at identifying the best solution in terms of the γ parameter. In addition, a first estimate of turbine design is performed with an in-house code. Finally, both an estimate of the system investment cost, Levelized Cost of Electricity (LCOE) and a review of future developments are reported.

2. Methodology

A thermodynamic analysis of CC-OTEC has first been conducted to highlight the main features of this kind of plants. The theoretical limitations of OTEC have been initially assessed through the study of ideal cycles performance for typical seawater inlet temperatures. The effect of cold/warm seawater temperature rise/drop across the heat exchangers on the plant net specific work was investigated