Energy Conversion and Management 115 (2016) 276–287

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Thermoeconomic optimization of a Kalina cycle for a central receiver concentrating solar power plant

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A R T I C L E   I N F O

Article history:
Received 16 October 2015
Accepted 21 February 2016

Keywords:
Kalina cycle
Ammonia-water mixture
Thermoeconomic optimization
Concentrating solar power
Central receiver

A B S T R A C T

Concentrating solar power plants use a number of reflecting mirrors to focus and convert the incident solar energy to heat, and a power cycle to convert this heat into electricity. This paper evaluates the use of a high temperature Kalina cycle for a central receiver concentrating solar power plant with direct vapour generation and without storage. The use of the ammonia-water mixture as the power cycle working fluid with non-isothermal evaporation and condensation presents the potential to improve the overall performance of the plant. This however comes at a price of requiring larger heat exchangers because of lower thermal pinch and heat transfer degradation for mixtures as compared with using a pure fluid in a conventional steam Rankine cycle, and the necessity to use a complex cycle arrangement. Most of the previous studies on the Kalina cycle focused solely on the thermodynamic aspects of the cycle, thereby comparing cycles which require different investment costs. In this study, the economic aspect and the part-load performance are also considered for a thorough evaluation of the Kalina cycle. A thermoeconomic optimization was performed by minimizing the levelized cost of electricity. The different Kalina cycle simulations resulted in the levelized costs of electricity between 212.2 $\$\,MWh^{-1}$ and 218.9 $\$\,MWh^{-1}$. For a plant of same rated capacity, the state-of-the-art steam Rankine cycle has a levelized cost of electricity of 181.0 $\$\,MWh^{-1}$. Therefore, when considering both the thermodynamic and the economic perspectives, the results suggest that it is not beneficial to use the Kalina cycle for high temperature concentrating solar power plants.

1. Introduction

Concentrating solar power (CSP) plants are regarded as a viable solution for large scale clean electricity production [1]. One of the biggest challenges faced by the CSP industry today, as compared with the contemporary fossil fuel based alternatives, is the high cost of electricity production. A CSP plant uses a number of reflecting mirrors to focus and convert the incident solar energy to heat, and a power cycle to convert this heat into electricity. In addition, a thermal energy storage system could also be present to store excess heat and use it in times of little or no sunshine. The large investment costs of the CSP plants can be driven down by research in any of these areas through the development of more cost-effective components and improved system designs. One such possibility is the use of ammonia-water mixtures in the CSP plant with a Kalina cycle. The Kalina cycle was introduced in 1984 [2] as an alternative to the conventional steam Rankine cycle to be used as a bottoming cycle for combined cycle power plants. The composition of the ammonia-water mixture used in the cycle is defined by the *ammonia mass fraction*, i.e. the ratio of the mass of ammonia in the mixture to the total mass of the mixture. The change in the mixture composition affects the thermodynamic and the transport properties of the mixture [3]. Since its introduction, several uses for the Kalina cycle have been proposed in the literature for low temperature applications. Examples include their use in geothermal power plants [4], for waste heat recovery [5–8], for exhaust heat recovery in a gas turbine modular helium reactor [9], in combined heat and power plants [10,11], with a coal-fired steam power plant for exhaust heat recovery [12], as a part of Brayton-Rankine-Kalina triple cycle [13], and in solar plants [14–16]. For high temperature applications, the Kalina cycles have been investigated to be used as gas turbine bottoming cycles [17–20], for industrial waste heat recovery, biomass based cogeneration and gas engine waste heat recovery [21], for direct-fired cogeneration applications [22], and in CSP plants [23–26].

The feasibility of using ammonia-water mixtures at high temperatures has been questioned due to the nitridation effect resulting in the corrosion of the equipment [27]. However, the use of an ammonia-water mixture as the working fluid at high temperature

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http://dx.doi.org/10.1016/j.enconman.2016.02.063
0196-8904/

Nomenclature

A	area (m^2)
α_{rec}	receiver absorptivity
C	cost ($)
$\hat{C}$	specific cost ($ kW^{-1})
CRF	capital recovery factor
CSP	concentrating solar power
D	diameter (m)
DNI	direct normal irradiance (W m^{-2})
E	electricity (MWh)
η	efficiency
f	factor, defined locally where used
F_{cu}	copper loss fraction
GA	genetic algorithm
H	height (m)
k_d	real debt interest rate
k_i	insurance rate
k_{tur}	turbine constant (kg $K^{0.5}$ s^{-1} bar^{-1})
LCOE	levelized cost of electricity ($ MWh^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
N	rotation speed (rpm)
N_p	plant lifetime in years
O&M	operations and maintenance
p	pressure (bar)
π	universal constant, 3.1416
$\dot{Q}$	rate of heat transfer (MW)
ρ_{col}	heliostat mirror (collector) reflectivity
T	temperature (°C)
$\overline{T}$	average temperature (°C)
U	overall heat transfer coefficient (W m^{-2} K^{-1})
$\dot{W}$	mechanical or electrical power (MW)
X	vapour quality (kg kg^{-1})
x	ammonia mass fraction (kg^{-1})
ζ	relative load

Subscripts and components

abs	absorbed energy by receiver working fluid
atm	atmospheric transmittance
blo	blocking
cd	condenser
CF	cost function
cln	mirror cleanliness
cnt	contingency
col	heliostat mirror collector
cos	cosine effect
cw	condenser cooling water
d	design
el	electrical equipment and material
eqp	power cycle equipment
fix	fixed
gen	generator
hx	heat exchanger
inc	energy available on the receiver surface before receiver thermal loss
insc	instrumentation and control
inst	installation
inv	investment
is	isentropic
land	required land area
loss	loss
m	mechanical
M&S	Marshall and Swift equipment cost index
min	minimum
misc	power cycle miscellaneous cost
mx	mixer
net	net electrical power output
PC	power cycle
pip	piping
pp	pinch point
pres	pressure
pu	pump
re	recuperator
rec	solar central receiver
sep	separator
SF	solar field
sha	shadowing
site	plant site improvement
sol	available solar energy
spg	spillage
spl	splitter
temp	temperature
th	thermal
thv	throttle valve
tow	tower
tur	turbine
var	variable
y	yearly or annual

has been successfully demonstrated at the Canoga Park demonstration plant with turbine inlet conditions of 515 °C and 110 bar [28]. Moreover, a patent by Kalina [29] claims the stability of ammonia-water mixtures along with the prevention of nitridation for plant operation preferably up to 1093 °C and 689.5 bar using suitable additives. Water itself prevents the ammonia in the mixture from corroding the equipment up to about 400 °C, and above this temperature the amount of the additive is far below the damage threshold [30].

The motivation behind the current study is that the irreversibility during a heat transfer process can be reduced by using a zeotropic mixture, which evaporates and condenses at a varying temperature, contrary to the isothermal evaporation and condensation of a pure fluid [31]. In addition, using a mixture instead of a pure fluid presents an additional degree of freedom in terms of varying the mixture composition in order to obtain better performance from the power cycle. In the previous studies, the Kalina cycle has been evaluated primarily considering the thermodynamic performance of the cycle based on the cycle energy and exergy efficiencies. The reduction in the irreversibility during the heat transfer process with a fluid mixture however comes at a price of increased heat exchanger areas and the need to use a complex cycle layout. These compromises have economic consequences as compared with using a pure fluid. This study focuses on the quantification of these consequences. The primary objective of this paper is to thermoeconomically evaluate the use of a Kalina cycle for a central receiver CSP plant with direct vapour generation and without storage. The presented thermoeconomic optimization methodology includes (1) the thermodynamic design of the Kalina cycle and the solar field, (2) their part-load performances, and (3) the economic model including the cost functions for estimating the capital investment and the operations and maintenance (O&M) costs. The results from the thermoeconomic optimization of the Kalina cycle are presented and briefly compared with those