Energy Conversion and Management 157 (2018) 631–643

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Thermodynamic analysis of a combined power/refrigeration cycle: Combination of Kalina cycle and ejector refrigeration cycle

Candeniz Seckin

Department of Mechanical Engineering, Faculty of Engineering, Marmara University, Goztepe Campus, Istanbul 34722, Turkey

ARTICLE INFO

Keywords:
Kalina cycle
Ejector refrigeration cycle
Combined refrigeration and power cycle
Cogeneration
Thermodynamic analysis

ABSTRACT

In the present study, a new power and refrigeration cycle is investigated which is a combination of a Kalina cycle and an ejector refrigeration cycle (ERC). In the proposed configuration of the combined cycle, an ejector refrigeration cycle is inserted into the Kalina cycle to recover heat from ammonia poor solution which leaves the separator at high temperature/pressure and does not contribute to power generation in Kalina cycle Working fluid of the Kalina cycle and ERC are ammonia-water solution and R134a, respectively. The combined cycle is simulated by EES software and details of the applied mathematical model and developed simulation program are extensively reported. The effect of five key operational parameters of the combined cycle (i.e. turbine inlet pressure, turbine inlet temperature, concentration of ammonia-water basic solution, condenser outlet temperature and pressure of refrigerant in heat exchanger) on the combined cycle performance parameters (refrigeration capacity, power production, thermal efficiency, exergy of produced power, exergy of refrigeration and exergy efficiency) is analyzed and physical mechanisms behind the determined results are reported. Additionally, variation of performance parameters with heat exchanger pressure is examined with different refrigerants (R134a, R152a and R290) to determine the effect of refrigerants on system performance. The results show that thermal efficiency of the combined cycle increases with increasing turbine inlet temperature and concentration of ammonia-water solution but decreases with rising condenser outlet temperature and heat exchanger pressure. A maximum thermal efficiency point is determined in the analyzed range of the turbine inlet pressure. Exergy efficiency increases with rising turbine inlet pressure, turbine inlet temperature and concentration of ammonia-water solution but decreases with increasing condenser outlet temperature and heat exchanger pressure. Refrigeration capacity and thermal efficiency results of the combined cycle are the highest for the operation of ERC with R290 and the lowest with R134a. Exergy efficiency is the lowest for ERC operation with R290 and the highest with R134a.

1. Introduction

Energy is strongly necessary and directly related with economic and social development of countries and well-being of human beings. Due to the increasing depletion rates of high quality energy sources, the rapid growth in population and growing rate of industrialization, efficient use of energy and minimum consumption of natural energy sources are regarded as critical issues of industrial development and environmental protection. In the sense of more efficient energy-resource conversion, the combined cycles of cooling and power display higher efficiency with respect to conventional cycles and this makes the combined cycles (cogeneration cycles) promising as a future trend of power and refrigeration production [1–3].

In a conventional steam power cycle (Rankine cycle), pure fluids are used as working fluid (usually water) which leaves the boiler at high temperature/pressure and expands in a turbine to produce power. Instead, using a binary mixture in the cycle provides a better temperature match than that of pure working fluids in heat transfer processes due to the variable-temperature phase change capability of binary mixtures. Due to better temperature match of the binary mixture working fluid, less irreversibility occurs in heat transfer process and total cycle efficiency gets higher. For power generation and refrigeration, among possible candidates of binary mixtures, the most known and used binary mixture is ammonia–water mixture in both of the industrial applications and academic studies. Ammonia–water mixture is also the working fluid of the analyzed power production cycle (Kalina cycle) of this present study [1,4,5].

Maloney and Robertson [6] performed one of the first studies of power cycle with binary fluid: absorption power cycle with ammonia–water mixture as the working fluid. Then, in the early 1980s, Kalina [7,8] introduced his absorption power cycle (Kalina cycle) with a novel configuration which uses ammonia–water mixture and offers higher

---

E-mail address: candeniz.seckin@marmara.edu.tr.

https://doi.org/10.1016/j.enconman.2017.12.047
Received 7 August 2017; Received in revised form 12 December 2017; Accepted 13 December 2017

Nomenclature

A	cross-sectional area (m^2)
C	speed of sound (m/s)
$\dot{E}x$	rate of exergy (kW)
h	specific enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
M	mach number, molecular weight
P	pressure (kPa)
q	quality
$\dot{Q}$	rate of heat transfer (kW)
s	specific entropy (kJ/kg K)
T	temperature (°C)
V	velocity (m/s)
v	specific volume (m^3/kg)
w	entrainment ratio
$\dot{W}$	power (kW)
x	concentration
1,2,3 … ,21	number of state-points in Fig. 1

Greek symbols

ψ	specific exergy (kJ/kg)
η	efficiency
ρ	density

Subscripts

0	dead state
a	mixed flow/cross section a in Fig. 3
b	shocked flow/cross section b in Fig. 3
cc	combined cycle
cond-I	condenser I
cond-II	condenser II
d	diffuser
dest	destroyed
eva	evaporator
ex	exergy
H20	water
in-I	input in the HE-I
in-II	input in the HE-II
is	isentropic
K	Kalina cycle
m	primary nozzle exit
mass	mass transfer
net	net
NH3	ammonia
p-I	pump I
p-II	pump II
Q	heat transfer
ref	refrigeration
s	secondary nozzle exit
tot	total
tur	turbine
W	work interaction

Abbreviations

ERC	ejector refrigeration cycle
HE I	heat exchanger I
HE II	heat exchanger II
HTR	high-temperature recuperator
LTR	low-temperature recuperator
TTD	terminal temperature difference

efficiency. After that, numerous studies have investigated the performance of Kalina cycle under different conditions and have reported the higher performance of Kalina cycle relative to that of conventional power cycles. [9–12]. The proposed configuration by Kalina can be regarded as further development of Rankine cycle and absorption power cycle which also utilize from the above mentioned characteristic advantage of the binary mixture use. Hence, irreversibility of the cycle is kept low but efficiency is higher [13].

Regarding the combined cycles which use ammonia–water mixture as working fluid and generate power and refrigeration concurrently, Goswami and Xu [14] proposed a new combined cycle of power/cooling generation (Goswami cycle) in which the ammonia-rich vapor separated by a rectifier unit is employed as the turbine working fluid to generate power, and then the turbine exhaust provides cooling by transferring sensible heat to the chilled water. Later, power generation in the turbine of the cycle is further increased by slight modification of Goswami cycle configuration such as installing a superheater before the turbine to increase the turbine inlet temperature and pressure [15]. In the literature, parametric analysis [16,17], exergy based analysis [18–20], parametric optimization [21–24], thermoeconomic analysis [25] and experimental studies [26,27] are carried out for Goswami cycle. In some studies, several design modifications are applied to improve the refrigeration and power generation capacity of the Goswami cycle [28–31]. Besides Goswami cycle, other combined cooling and power cycle configurations which use ammonia water mixture as the working fluid are presented by Liu and Zhang [32], Zhang and Lior [33,34], Wang et al. [35].

Studies of Kalina cycle based combined cycles which produce power and refrigeration output, are also seen in the literature. Zheng et al. [13] added a condenser, an evaporator and a rectifier to the Kalina cycle to have higher concentration of ammonia in the working fluid and to enhance the refrigeration capacity. Yu et al. [36] proposed a novel combined cooling/power generation system which consists of a modified Kalina cycle and an ammonia absorption cooling cycle. The cycles are interconnected by mixers, splitters, absorbers and heat exchangers. The proposed combined cycle can produce different ratios of cooling and power. Jing and Zheng [37] presented a new power/cooling cogeneration cycle which is a combination of Kalina cycle and the double-effect ammonia–water absorption refrigeration cycle and analyzed heat-to-power ratio and exergy efficiency improvement of the combined cycle. Hua et al. [38] combined a modified Kalina cycle and an ammonia-water absorption refrigeration cycle to generate power and cooling output. Analysis of the impact of key parameters on the thermal and exergy efficiencies is presented. Srinivas et al. [39] analyzed cooling/power cogeneration cycle which is designed by coupling a Kalina cycle with a absorption refrigeration cycle. They reported increased energy utilization factor for the cogeneration cycle and determined the operational conditions of maximum performance. Then Shankar and Srinivas [40,41] proposed a new cooling/power cogeneration cycle (Srinivas cycle) in which the working fluid (ammonia–water mixture) is condensed at the turbine exit to the phase of the saturated liquid and then is brought to a lower pressure before entering into the evaporator to increase the cooling capacity of the cycle. Zare [42] conducted a comparative thermodynamic analysis and optimization for two different tri-generation cycles: Kalina cycle based and organic Rankine cycle (ORC) based tri-generation cycles driven by geothermal heat. A LiBr/water absorption chiller and a water heater are coupled to the tri-generation cycles to produce cooling and heating. The Kalina cycle based tri-generation is more efficient than the other cycle in terms of exergy efficiency. Another Kalina cycle based trigeneration