Energy Conversion and Management 162 (2018) 225–238

Contents lists available at ScienceDirect

Energy Conversion and Management

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

A novel Kalina power-cooling cycle with an ejector absorption refrigeration cycle: Thermodynamic modelling and pinch analysis

Jouan Rashidi, ChangKyoo Yoo*

Dept. of Environmental Science and Engineering, College of Engineering, Center for Environmental Studies, Kyung Hee University, Seocheon-dong 1, Giheung-gu, Yongin-Si, Gyeonggi-Do 446-701, Republic of Korea

ARTICLE INFO

Keywords:
Absorption
Ejector
Kalina cycle
Heat pinch
Power and cooling cogeneration

ABSTRACT

A new power and cooling cogeneration cycle is proposed that combines the Kalina power cycle and the ejector absorption refrigeration cycle with an ammonia-water mixture as the working fluid. The proposed system, Kalina power-cooling with an ejector cycle (KPCE), originates from the Kalina power and cooling cycle (KPCC) and introduces an ejector before the evaporator. Thermodynamic analyses from the viewpoints of energy efficiency, as well as comparisons between KPCC and KPCE under the same initial conditions, were conducted for the cycles' refrigeration output and thermal efficiency. Energy analysis results showed that the KPCE provides a performance improvement without greatly increasing system complexity. At the same power production level, the refrigeration output and thermal efficiency of KPCE is 13.5% higher and 17% more than KPCC, respectively. Energy losses due to inefficient heat recovery design of the system are identified by cross heat pinch analysis. All three preheaters of the system showed an inefficient design of heat recovery. After redesigning, power, and power-cooling efficiencies showed 7% and 4.3% increases, respectively. The effect of four important input parameters including three pressure levels and ammonia mass fraction on the KPCE performance are investigated to optimize the system. The optimized KPCE performance improved by 17.9% and 13.6% for power and power-cooling efficiency while the total annual cost of the system could decrease by 6.8%.

1. Introduction

Industrial waste heat is a low quality free energy source that can be recovered and converted into power and/or cooling. Several researchers have investigated the performance of power systems using low grade heat sources, and most concentrated on Rankine, Kalina, and other cycles with unconventional working fluids [1,2]. Various thermodynamic cycles have been developed to utilize and recover low-grade heat for cooling purpose, such as absorption, adsorption, desiccant, and ejection cycles [3]. Dai et al. proposed a system that combined the Rankine cycle and the ejector-refrigeration cycle by adding a turbine between the generator and the ejector [4]. Alexis [5] performed the first law analysis of a Rankine cycle generating 2 MW combined with an ejector-refrigeration cycle. Li et al., proposed a Kalina cycle (KC) where an ejector was used as a substitute for the throttle valve and the absorber [6]. Since the ejector could increase the working pressure difference, the cycle could obtain a higher power output and thermal efficiency. Wang et al. proposed a combined power and refrigeration cycle where an ejector is placed between the rectifier and the condenser of the Rankine cycle thereby improving the performance of the cycle using the ejector.

Low quality and free energy sources such as industrial waste heat can be recovered and used in both power and cooling production systems. Several researchers have studied power production performance using low grade heat sources while concentrating on unconventional working fluids such as ammonia-water mixture in Rankine, Kalina, or other cycles [7,8]. Ammonia-water evaporates and condenses as a non-azeotropic mixture over a range of temperatures, and is therefore able to achieve a better temperature match between the working substance and heat sources.

The Kalina cycle KC, introduced by Alexander Kalina, is a fairly new thermodynamic power cycle using an ammonia-water mixture with the potential of efficient energy conversion of low-grade heat sources, including low-temperature geothermal energy [9], solar energy [10], and industrial waste heat [11].

Power and cooling cogeneration systems utilizing low grade heat sources have been studied by various researchers. Rashidi et al. introduced two highly efficient power-cooling cycle integrating Kalina and absorption refrigeration cycles, KPCC (Kalina power-cooling cycle) and KLACC (Kalina lithium-bromide absorption cooling cycle), to

* Corresponding author.
E-mail address: ckyoo@khu.ac.kr (C. Yoo).

https://doi.org/10.1016/j.enconman.2018.02.040
Received 9 October 2017; Received in revised form 26 January 2018; Accepted 9 February 2018

Nomenclature

Abbreviations	Explanation
ABS	Absorber
ACC	Annual capital cost
C	Condenser
DES	Desorber
EV	Expansion valve
EVAP	Evaporator
FT	Flash tank
FTP	Flash tank preheater
KC	Kalina cycle
KPCC	Kalina power - cooling cycle
KPCE	Kalina power-cooling with ejector
PH	preheater
SH	Superheater
PA	Pinch analysis
TAC	Total annual cost
Symbol	Explanation
fr	Mass ratio
h	Enthalpy (kJ/kg)
η	Efficiency
$\dot{m}$	Mass flow rate (kg/s)
P1	Pump1
P2	Pump2
Q	Heat (kW)
S	Entropy (kJ/kg K)
T	Temperature (K)
W	Power (kW)
X	Ammonia mass fraction
Y	Exergy ratio

Indexes

e	Outlet
i	Inlet
k	kth component
L	Loss
Out	Outlet
p	power
p,c	Power-cooling
Q	Heat
ref	Refrigeration
W	Work

produce both outputs simultaneously [12]. They reported a power-cooling efficiency of 18.8% and 20.2% for KPCC and KLACC respectively. The exergetic efficiency and unit cost of power-cooling generation from exergoeconomic analyses for both KPCC and KLACC systems are studied by Rashidi et al. [13]. They concluded that KPCC system can be introduced as the best power-cooling system with 20.5% lower unit cost of product and less complexity, but the performance should be optimized. With the same purpose, the performance of a combined Rankine cycle with an ejector has been investigated [14]. The performances of different working fluids in a combined organic Rankine cycle and ejector refrigeration cycle have been studied by Habibzadeh et al. [15].

The Pinch analysis (PA) is a powerful analytical method to identify and select concrete technical solutions for improving efficiencies and providing optimum manufacturing solutions [16]. PA with the idea of setting targets prior to design was first introduced and developed in the late 1970s and has reported significant changes in energy saving and several applications in chemical process industries [17]. Researchers have performed studies using PA in various power plants to simulate and modify the existing sites [18].

According to the literature, performance studies of a combined Kalina and ejector cycle as a power-cooling cogeneration cycle are rare. Some studies have applied the heat integration between Kalina power cycle and ejector absorption refrigeration cycle where power and cooling are generated in two separated sub-cycles. Some other studies proposed a combined cycle as a single cycle to produce power and cooling simultaneously with a where the turbine exhaust enters the ejector as the primary fluid. The aim of this article is to propose an optimized and high efficient combined power and cooling cycle with an ejector refrigeration cycle that utilizes the ammonia water solution. In this study, the Kalina power-cooling cycle with an ejector (KPCE) is introduced. Unlike most of the studies, the KPCE system is able to produce power and cooling in one single cycle simultaneously. Also it is proposed to place the ejector after the condenser of the cycle. The KPCC system which was mentioned before can produce both power and cooling but the efficiency is not high enough because of heat losses, not optimized initial input parameters, and low cooling generation. In order to improve the KPCC system, a new cycle (KPCE) is proposed to use the ejector in the cycle since the ejector is able to decrease losses while expansion of the working fluid and recover a portion of working fluid as the secondary fluid.

To analyze the KPCE the performance of the system is subjected to energy analysis to find the energy losses. KPCE is then compared with the KPCC system to find the effect of ejector on KPCC. Additional losses of energy due to inefficient heat recovery design of the system are identified through heat pinch analysis. Pinch point and Cross pinch heat exchangers are identified. According to these losses obtained from energy and pinch analyses, the process is redesigned to improve the performance of the equipment and eliminate cross heat transfer. For the final step the effect of initial input parameters on the performance and total annual cost of KPCE are investigated and subject to the best performance and lowest total cost the system is optimized.

2. Materials and methods

2.1. System configuration

Fig. 1a shows a schematic diagram of the KPCC (Kalina power-cooling cycle) using an ammonia – water mixture as the working fluid and a low-temperature heat source [19]. KPCC consists of two loops, the refrigeration loop and the power loop. The absorber, flash tank, and condenser play roles in both loops. A portion of the condensed solution is sent to the evaporator to generate cooling. Indeed, the cooling system operates based on an ammonia-water absorption chiller. The cooling load of the system can be controlled by changing the mass flow rate through the evaporator and the evaporator pressure. The cycle works with three different ammonia concentrations. The primary concentration (X_{ABS}) with an intermediate range (47%) at state 1 leaves the absorber and is separated through the flash tank to the highest (X_{TUR}) and lowest (X_{LOW}) concentration streams (step 4 → 5, 15). The solution with a concentration of X_{TUR} is divided into two portions to produce power and cooling through the turbine and evaporator, respectively. Cycling the working fluid heat recovery happens in two heat exchangers (FTP1 and FTP2) before separation in the flash tank, and in another heat exchanger (PH) before condensation. This system is a flexible cycle, switching between a power ($fr = 0$), a power-cooling cogeneration ($0 < fr < 1$), and a cooling generation cycle ($fr = 1$).

Fig. 1b represents a schematic of the proposed Kalina power-cooling cycle with an ejector (KPCE) system. The cycle is a combination of KC and ejector absorption refrigeration cycles to simultaneously produce power and cooling. The working fluid after pumping to intermediate pressure (4.7 bar) and heating in two preheaters (FTP1 and FTP2)