Applied Energy 222 (2018) 1–12

Contents lists available at ScienceDirect

Applied Energy

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

Thermodynamic analysis of a novel sodium hydroxide-water solution absorption refrigeration, heating and power system for low-temperature heat sources

Zhaoli Zhang[a,b], Sami M. Alelyani[b], Nan Zhang[c], Chao Zeng[a], Yanping Yuan[a,*], Patrick E. Phelan[b,*]

[a] School of Mechanical Engineering, Southwest Jiaotong University, Chengdu 610031, China
[b] School for Engineering of Matter, Transport & Energy, Arizona State University, Tempe, AZ 85287-6106, United States
[c] State Key Laboratory of Aerodynamics, Aerodynamics Research and Development Center, 621000 Mianyang, China

HIGHLIGHTS

- A novel polygeneration system for producing cooling, heating and power is proposed.
- Sodium hydroxide-water is used as the working pair in absorption refrigeration.
- R218 ORC generates power with driven heat source from reaction heat in an absorber.
- Cooling, heating and power capacity are 945.2, 460.8 and 39.41 kW in a condition.
- PESR between proposed system and three separated systems can reach up to 0.4889.

ARTICLE INFO

Keywords:
Thermodynamic analysis
Sodium hydroxide-water solution
Absorption refrigeration
Organic Rankine cycle
Low-temperature heat source

ABSTRACT

A novel sodium hydroxide-water solution absorption refrigeration, heating and organic Rankine cycle power system is proposed for low-temperature heat source utilization. The sodium hydroxide-water solution absorption refrigeration is employed as top cycle which directly absorbs heat from low-temperature heat source. While R218 organic Rankine cycle and heating subsystem are adopted to produce power and heating as designed in bottom cycles. Under the considered condition, model results indicate that refrigeration, heating and electricity efficiency are 0.8244, 0.4019 and 0.03437 with the capacity of 945.2, 460.8 and 39.41 kW, respectively. Energy and exergy efficiency of refrigeration, heating and electricity are also theoretically analyzed with various condensation temperature, evaporation temperature, turbine inlet pressure, split ratio and mass fraction of rich sodium hydroxide solution. Sensitivity of parameters to system performance is also analyzed and results indicate that energy and exergy efficiency are remarkably influenced by operating parameters. A comparison between the proposed system and three independent electrical refrigeration, heating and power systems shows that the proposed system has superior performance and the maximum primary energy saving ratio can reach approximately 0.4889. In conclusion, with the multi-productions of refrigeration, heating and electricity, the proposed polygeneration system provides a more rational and effective energy utilization from a single low temperature heat source at suitable level.

1. Introduction

Rapid economic development, fast population rise and continuous living standard growth have resulted in serious energy-related problems, such as increasing energy demands, deficient energy resources and rising energy cost, etc. Fossil fuels, primarily coal, oil and natural gas, are still identified as the main energy resources and approximately 80% of the worldwide electricity is generated from the combustion of fossil fuels [1]. Residential and commercial air conditioning and refrigeration are commonly accomplished by traditional vapor compression systems based on electrically-driven compressor chillers, and such vapor compression systems consume approximately 15% of all electricity [1,2]. Simultaneously, the exhaust gas emissions caused by electric generation contributes significantly to environmental concerns

* Corresponding authors.
E-mail addresses: ypyuan@home.swjtu.edu.cn (Y. Yuan), phelan@asu.edu (P.E. Phelan).

https://doi.org/10.1016/j.apenergy.2018.04.008
Received 29 December 2017; Received in revised form 2 April 2018; Accepted 3 April 2018

Nomenclature

Abbreviation

ABS	absorber
CON	condenser
COP	coefficient of performance
EVA	evaporator
EV	expansion valve
GEN	generator
HX	heat exchanger
ORC	organic Rankine cycle
PESR	primary energy saving ratio
RSHS	rich sodium hydroxide solution
TAN	solution tank
WSHS	weak sodium hydroxide solution

Symbols

mf	mass fraction
Q	heat capacity
S	sensitive factor
T	temperature
W	power
β	split ratio
η	efficiency
ψ	flow exergy

Subscripts

A	absorber
B	boiler
C	condenser
E	evaporator
el	electricity
ex	exergy
G	generator
H	heating
in	inlet
out	outlet
P	pump
R	refrigeration
sep	separated system
t	total
th	thermal

[3–7]. In light of these difficult issues, it is urgent to seek other available renewable energy sources to address the increasing cooling demand and energy crisis.

Absorption cooling systems is an effective approach to produce refrigeration capacity with driving heat from low-temperature heat sources [8–16]. Generally, heat reservoirs with temperatures approximately under 200 °C are defined as low-temperature sources. They are extensively distributed in solar radiation, geothermal energy and industrial residential and waste heat, and can hardly be efficiently converted through traditional methods due to the less exergy density [11,17–22]. Accordingly, absorption cooling system reduces energy consumption the summer by replacing electrically driven compressor chillers with thermally driven chillers. Meanwhile, it can also be concisely coupled with other thermodynamic cycles for various functions. With integration of a suitable heat exchanger, the combined system can achieve heat transfer of low-temperature thermal energy to domestic hot water [23,24]. When integrated with a turbine, the combined system enables the generation of electricity which is usually accomplished by an organic Rankine cycle (ORC) [25–27]. The combined system also enables to produce fresh water from seawater if it is connected to multi effect distillation (MED) equipment [28,29]. In addition, a solar-driven combined system can also be extended to operate after sunset or cloudy weather by incorporating an energy storage subsystem [30,31]. Featuring these outstanding advantages, the combined system with integration of absorption refrigeration, heating, power, desalination or energy storage functions will present significant potential in further applications of low-temperature heat sources.

Many studies have evaluated combined systems containing above functions, which often are called polygeneration systems. The most common is referred as combined cooling, heating, and power (CCHP) system [32,33]. Wang et al. [34] optimized the capacity and operation of a CCHP system by a genetic algorithm based on the thermal demand of buildings. Results indicated that Coefficient of Performance (COP) of the CCHP system was maximized at a particular capacity and the ratio of electricity to cool load. Primary energy savings and carbon dioxide emissions reduction of the CCHP system remained unchanged. Zhang et al. [35] proposed several novel combined systems with ammonia-water refrigeration and Rankine cycles. That cogeneration system had admirable performance, with energy and exergy efficiencies of 28% and 55–60%, for the base case studied at a maximum heat input temperature of 450 °C. Energy efficiency could rise to 57% when using exhaust heat from topping gas turbine power plants. Xu et al. [36] presented a CCHP system and described the key scientific problems of a distributed energy system and the integration principles of a CCHP system with lithium bromide-water solution and gas turbine. Results indicated that the energy-saving rate of the CCHP system with complementary fossil and renewable energy could reach 17.8% over the entire year. When integrated with desalination, the energy-saving rate of this novel system was approximately 30.4%.

Systems obtaining the functions of refrigeration, power and desalination also have been proposed. Alelyani et al. [37] conducted a techno-economic analysis of combined ammonia-water absorption refrigeration and desalination. Results indicated that the total exergy destruction of the combined systems containing an MED unit driven by either a single- or double-stage NH_3-H_2O refrigeration system decreased by 55% relative to stand-alone systems. The unit product cost of cooling decreased significantly by 43%, while the unit product cost of the produced water increased by only 19% and 3% for single- and double-stage NH_3-H_2O-MED systems, respectively. Hogerwaard et al. [38] designed a multigeneration system integrating a solar-driven gas turbine with an ORC, ammonia-water absorption refrigeration, single-stage flash desalination and direct space heating. The proposed system exhibited respectively energy and exergy efficiencies of 28.4% and 27.0%, and provided a promising approach for more sustainable products from a single heat source for communities or small commercial applications.

Finally, other literature involved combined cooling, heating and power systems with integration energy storage. Wang et al. [39] performed multi-objective optimization to obtain the optimum performance of a solar-powered CCHP system using flat-plate solar collectors and obtained the system performance from thermodynamic and economic aspects. For the system operating in the power mode, combined heat and power mode and combined cooling and power mode, the optimum average useful output and total heat transfer area were 6.40 kW and 46.16 m^2, 5.84 kW and 58.74 m^2 and 8.89 kW and 38.78 m^2, respectively. Gadhamshetty et al. [40] integrated thermal energy storage into a dual-purpose power plant. Providing cooling water for condensers in desalination and the power plant, thermal energy storage improved the effective thermal performance of the power plant and multi-effect evaporation. Results showed that thermal energy storage saved power loss of 2.5% in a combined cycle power plant in