Energy Conversion and Management 134 (2017) 208–220

Contents lists available at ScienceDirect

Energy Conversion and Management

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

# Exergeoconomic analysis and optimization of a novel cogeneration system producing power and refrigeration

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ARTICLE INFO

*Article history:*
Received 23 September 2016
Received in revised form 24 November 2016
Accepted 3 December 2016

*Keywords:*
Thermoeconomic analysis
Ammonia-water
Geothermal
Thermal and exergy efficiencies
Cogeneration
Optimization

ABSTRACT

A novel combined cooling and power cogeneration system driven by geothermal hot water is proposed. The system, which is a combination of an organic Rankine cycle and an absorption refrigeration cycle, is analyzed and optimized from the viewpoints of thermodynamics and economics. The working fluid in organic Rankine cycle is ammonia and in the refrigeration cycle is an ammonia-water solution. Parametric studies are performed to identify decision parameters prior to optimization. In optimizing the system performance three design cases i.e. designs for maximum first law efficiency (case1), maximum second law efficiency (case2) and minimum total product unit cost (case3) are considered. The results show that the total products unit cost in case3 is around 20.4% and 24.3% lower than the corresponding value in case1 and 2, respectively. The lower product unit cost in case3 is accompanied with an expense of 10.21% and 4.5% reduction in the first and second law efficiencies, compared to case1 and 2, respectively. The results also indicate that concerning the costs associated with capital and exergy destruction costs of components, the priority of components for modifications are the turbine, condenser and absorber. The last component in this order are the two pumps in the system.

## 1. Introduction

Utilization of low grade heat sources such as solar, geothermal, biomass and industrial waste heat is an important issue in overcoming the problems of energy shortage and environmental pollution. In this regard, cooling technologies activated by low-grade heat have attracted researchers' interest [1]. Different thermodynamic cycles have been proposed and investigated to operate with medium or low temperature heat sources [2]. A characteristic of these new cycles is the use of a binary mixture as working fluid causing an increased thermal efficiency because of its variable boiling temperature which leads to a better temperature matching and consequently a lower exergy destruction in heat exchangers [3]. Ammonia–water mixture is a binary natural refrigerant which is environmental friendly and have some excellent thermophysical properties. They are commonly used as working fluids in absorption refrigeration cycles, absorption power cycles, and combined power and cooling cycles. Compared with lithium-bromide absorption chillers, ammonia absorption refrigeration systems have a broader operation temperature range (approximately 60–10 °C) and can provide cold for industrial applications with an evaporation temperature of below 0 °C [4].

The use of binary mixtures as working fluids in organic Rankine cycles (ORC) have also been practiced in recent years [5]. It has been reported that using binary mixtures in the ORC and refrigeration systems results in achieving high efficiency in converting low-grade thermal energy to more useful forms of energy [6], and decreasing the cost of energy per unit capital expense. Goswami proposed a combined power/cooling cogeneration cycle with ammonia-water mixture as working fluid. This author and some other workers modified this cycle and carried out some parametric studies on it [7].

Zare et al. [8] investigated and optimized the performance of an ammonia-water power/cooling cogeneration cycle. Their results showed that, under economically optimized condition, the sum of products unit cost is 18.6% and 25.9% lower than the values obtained when the optimization is performed from the viewpoints of first and second laws of thermodynamics, respectively. Making use of mid-temperature waste heat, Han et al. [9] developed a cascaded refrigeration system including a compression refrigeration cycle and a conventional ammonia absorption refrigeration cycle. They reported a better thermal efficiency due to the cascade use of input heat. Jawahar et al. [10] introduced a combined power and cooling system which was based on a generator absorber heat exchanger (GAX) Kalina cycle. It was shown that about 20% of internal heat of the proposed cycle could be recovered by using the GAX heat exchanger. Wang et al. [11] developed a novel

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http://dx.doi.org/10.1016/j.enconman.2016.12.007
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**Nomenclature**

| | |
|---|---|
| $\dot{C}$ | cost rate ($\$\ h^{-1}$) |
| c | Cost per exergy unit ($\$\ GJ^{-1}$) |
| $\dot{E}$ | exergy rate (kW) |
| e | Specific exergy ($kJ\ kg^{-1}$) |
| h | specific enthalpy ($kJ\ kg^{-1}$) |
| M | molar |
| $\dot{m}$ | mass flow rate ($kg\ s^{-1}$) |
| P | pressure (bar) |
| s | specific entropy ($kJ\ kg^{-1}\ K^{-1}$) |
| T | temperature (°C *or* K) |
| $\dot{W}$ | power (kW) |
| U | overall heat transfer coefficient ($kW\ m^{-2}\ K^{-1}$) |
| X | ammonia concentration |
| Z | investment cost of component ($) |
| $\dot{Z}$ | investment cost rate of component ($\$\ h^{-1}$) |
| $e^0_{ch,H_2O}$ | standard chemical exergy($kJ\ mol^{-1}$) |

*Subscripts and abbreviations*

| | |
|---|---|
| 0 | ambient |
| ABS | absorber |
| ARC | absorption refrigeration cycle |
| BOI | boiler |
| CI | capital investment cost |
| ch | chemical |
| COD | condenser |
| CRF | capital recovery factor |
| cv | control volume |
| cw | cooling water |
| D | destruction |
| DEP | dephlepmator |
| EVA | evaporator |
| EEOD | exergy efficiency optimum design |
| EUF | energy utilization factor |
| EUFOD | energy utilization factor optimum design |
| EV | expansion valve |
| F | fuel |
| g | geothermal heat water |
| GEN | generator |
| $i_r$ | interest rate |
| L | loss |
| n | number of useful years |
| OHE | ORC heat exchanger |
| OM | operating & maintenance |
| ORC | organic Rankine cycle |
| P | product |
| ph | physical |
| PU | pump |
| pp | pinch point |
| RHE | reheating heat exchanger |
| SHE | solution heat exchanger |
| SP | splitter |
| TPCOD | total products cost optimum design |
| TIP | turbine inlet pressure |
| TIT | turbine inlet temperature |
| TUR | turbine |
| $r_F$ | flow division ratio |
| $r_{cF}$ | critical flow division ratio |

*Greek symbols*

| | |
|---|---|
| $\eta_{EX}$ | exergy efficiency |
| $\tau$ | annual plant operation hours |
| $\gamma_k$ | fixed cost operation and maintenance cost |
| $\omega_k$ | variable operation and maintenance cost |
| $R_k$ | all the other operation and maintenance costs |
| $\eta_{TUR}$ | turbine isentropic efficiency |
| $\eta_{PU}$ | pump isentropic efficiency |

adsorption cycle for cogeneration of electricity and refrigeration based on ammonia adsorption refrigeration system driven by the low grade heat source. They reported an exergy efficiency of 0.69 and a coefficient of performance (COP) of 0.77, respectively for the proposed cycle. An ammonia–water based system driven by mid/low-temperature heat source was suggested by Sun et al. [12] proposed for power and cooling cogeneration. The proposed system consisted of a Rankine and an absorption refrigeration cycles so that the condenser of refrigeration system is the evaporator of Rankine cycle. The high-temperature portion of waste heat is used for power generation, whereas the low-temperature part is utilized for refrigeration. They reported that the equivalent heat-to-power and exergy efficiency of the cogeneration system can reach 18.6% and 42.0%, respectively. Yu et al. [13] proposed and investigated a cogeneration system with adjustable cooling to power ratio. In the proposed system, a modified Kalina cycle is combined with an ammonia absorption cooling cycle. They reported that the combined system efficiency and COP values are 6.6% and 100% higher than the corresponding values in the separate systems, respectively. Their results also showed that the cooling to power ratio in the proposed system can be adjusted in the range of 1.8–3.6 under the given operating conditions. Jing and Zheng [14] introduced a new power/cooling cogeneration system by combining the Kalina cycle and the double-effect ammonia–water absorption refrigeration (DAAR) cycle. They reported a heat-to-power and an exergy efficiency of 41.18% and 58.00%, respectively for the proposed system. The annual performance of a solar driven ammonia-water absorption power and cooling system in buildings with a biomass auxiliary system was investigated by Muye et al. [15]. They reported a yearly efficiency range of 59% - 63% for the scroll expander and an annual efficiency range of 6–8% for the system. The concluded that the annual solar contribution changes between 23 and 30% depending on the location of the system and evaporator temperature. Kim and Perez-Blanco [16] proposed a new cogeneration system activated by low-grade heat source. The system included an ORC for generating power and a vapor compression refrigeration cycle for producing refrigeration. The analysis is concluded for several different working fluids and reported that isobutene as working fluid brings about the best performance for the system. A combined cooling and power system employing an organic Rankine cycle and an ejector refrigeration cycle was suggested by Zhao et al. [17]. They concluded that, under optimized condition, the highest exergy destruction occurs in the vapor generator and the next two largest exergy destruction take place in the steam turbine and flashing device, respectively.

From the above review, it is evident that combining power and cooling generation systems have been the interest of researchers as it leads to an effective way of using energy sources. In the present work a novel combined system including an ORC and an ammonia-water absorption refrigeration cycle is proposed and analyzed in detail. Parametric studies are done to identify the decision parameters prior to the system performance optimization. The optimization is performed considering either the second low efficiency or product unit cost as an objective function.