Energy Conversion and Management 150 (2017) 800–813

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Principle investigation on advanced absorption power generation cycles

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A R T I C L E I N F O

Article history:
Received 9 December 2016
Received in revised form 2 February 2017
Accepted 25 February 2017
Available online 7 March 2017

Keywords:
Absorption power generation
Double-effect cycle
Half-effect cycle
Ejector-combined cycle
Efficiencies
Power output

A B S T R A C T

Aiming at exploring advanced absorption power generation (APG) cycles using ammonia-water as working solution, the present study has studied one double-effect, one half-effect and one ejector-combined APG cycles based on one of the most widely studied APG cycles – Kalina KCS-11. The performance of these advanced cycles were numerically analyzed and compared against KCS-11 in terms of power output, energy and exergy efficiencies. An optimal mass fraction of ammonia-water solution used in KCS-11 has been identified to achieve the maximum energy and exergy efficiencies, which were 0.09–0.14 and 0.65–0.72 respectively when using 70.0–100.0 °C boiling temperature; however, the corresponding power output was only 23.0–48.0% of its maximum potential. The double-effect APG cycle could effectively improve the energy and exergy efficiencies by 3.6–12.6%, 10.7–28.2% and 19.0–900.0% respectively when using 100.0 °C, 120.0 °C and 140.0 °C boiling temperature; but its power output capacity was about 43.0–63.0% lower. The half-effect cycle could provide larger pressure ratio for power generation, which amplified the power output by 50.0–85.0% but sacrificed its energy and exergy efficiencies by 4.0–45.0% compared to that of KCS-11. To pursue higher energy and exergy efficiencies without a bulky two-stage system, one can replace the throttling valve and mixer in KCS-11 by an ejector to form a ejector-combined APG cycle, which could improve the system energy efficiency by 2.9–6.8% when using 80.0–100.0 °C boiling temperature, while the power output capacity was only slightly influenced.

1. Introduction

The global fossil energy usage grows rapidly in the last few decades, resulting in severe economic and environmental issues. A great deal of research efforts have been made on using the enormous amount of renewable thermal energy sources, such as solar energy and geothermal energy, as well as industrial waste heat, directly or converting them to electricity through diverse technologies [1,2]. As one of effective and environmental-friendly technologies to recover low-grade heat, absorption power generation (APG) cycle has been investigated widely for decades [3,4]. The usage of binary working fluid leads to lower heat transfer temperature difference between the heat source and the working fluid, thereby reducing the thermodynamic irreversibility.

In a pioneering work on APG cycle using ammonia-water as working solution reported by Maloney and Robertson (M-R cycle) [5], a typical absorption refrigeration configuration was modified by removing the condenser and evaporator but connecting a turbine in between the generator and absorber. It was concluded that there was no significant thermodynamic advantage of such APG system over steam Rankine system. That was attributed to the much higher energy loss in the ammonia-water absorption process than that in pure water condensation process in steam Rankine system. Kalina [6] proposed an alternative APG cycle which added one condenser and one pump compared to the M-R cycle. Numerically analysis has revealed that the Kalina cycle can potentially generate 1.4 times power comparing to steam Rankine cycle using the same heat source [7]; compared to M-R cycle, the additional condenser introduces one extra degree of freedom to Kalina cycle, leading to lower energy loss in absorber and then higher cycle efficiency [8]. Based on the original Kalina cycle, various configurations have been proposed to form the Kalina cycle family, including KCS-11, KCS-12, KCS1-2, KCS-34, KCS-34g, and Kalina split-cycle system, where KCS-11 and KCS-34 are the two most widely investigated cycles [3].

KCS-11 has very similar configuration as M-R cycle, but replaces the absorber by one mixer and one condenser. Hettiarachchi et al. [9] concluded that KCS-11 generally had better heat source and working fluid utilization efficiencies comparing to organic Rankine cycle (ORC), and also there existed an optimal ammonia mass fraction of the basic working solution to yield best system energy efficiency at a given turbine inlet pressure. Sun et al. [10–12] numerically studied a solar-driven KCS-11 system with an auxil-

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http://dx.doi.org/10.1016/j.enconman.2017.02.078
0196-8904/

Nomenclature

h	enthalpy (J/kg)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (Pa)
$\dot{Q}$	heating rate (W)
T	temperature (°C)
ΔT_{LMTD}	logarithmic mean temperature difference (°C)
UA	heat exchanger performance (W/K)
V	flow velocity (m/s)
w	mass fraction (–)
$\dot{W}$	power output (W)
η	efficiency (–)

Subscripts

bas	basic
boi	boiler
d	diffuser
en	energy
ex	exergy
H	high pressure/temperature
l	liquid
L	low pressure/temperature
M	medium pressure/temperature
n	nozzle
pump	pump
re	recuperator
rec	rectifier
s	isentropic/suction
tur	turbine
v	vapour

iary super-heater placed at the upstream of the turbine, which could achieve an energy efficiency of 8.93%, about 21.8% higher than that of Rankine system under the same boundary conditions [11]. Singh and Kaushik [13] reported the utilization of KCS-11 in coal-fire steam power plant for waste heat recovery. KCS-11 cycle could have the maximum thermal efficiency at 12.95% when its turbine inlet pressure was at 40.0 bar and the basic working solution had the ammonia mass fraction at 0.8, ultimately the overall energy efficiency of the coal-fire power plant was improved by 0.277%. Elsayed et al. [14] revealed that the KCS-11 using the ammonia-water solution with 0.55 ammonia mass fraction could achieve 20.0–40.0% higher thermal efficiency than that of ORC under the conditions of 15.0 bar turbine inlet pressure, 100.0 °C heat source and 10.0 °C heat sink. He et al. [15] modified KCS-11 by substituting the throttle valve that located between the separator and the mixer for a two-phase expander to pursue more power output, as a result, 2.07–9.39% improvement in thermal efficiency was achieved when the turbine inlet pressure was in the range of 15.0–30.0 bar and the heat source temperature was at 127.0 °C.

Contrasted with KCS-11, KCS-34 has one more recuperator as low pressure recuperator located between the condenser and mixer [16–19], while in some studies it also has one more liquid-vapour separator before the condenser [16,18] which aims to achieve better heat and mass transfer in the condenser. KCS-34 has been applied in practice in a geothermal power plant in Húsavík, Iceland since 2000 [16], and the system using ammonia-water solution with ammonia mass fraction at 0.82 had an energy efficiency of 20.0–25.0% higher than that of ORC system. Many numerical or simulation studies about KCS-34 have been conducted, some have concluded the prominent superiority of KCS-34 to ORC with some case studies [16,17], while some argued about marginal efficiency improvement by KCS-34 and also expressed the concerns about the more complicated and costly configuration of KCS-34 [18,19].

On the other side, there are plenty of advanced absorption cycles [20,21], such as double-effect, half-effect, sorption-resorption, absorber-heat-recovery, ejector-combined absorption, and diffusion absorption, which are expected to work at higher efficiency or at larger temperature lifting or at other improved aspects. It is worthy of exploring the feasibility and application of such advanced absorption cycles to the APG cycle; however, except one publication on ejector-combined APG cycle [22], such investigation has not been reported yet according to the authors' best knowledge. The present work has studied three different advanced APG cycles based on KCS-11, including one double-effect cycle, one half-effect cycle and one ejector-combined cycle, the corresponding performance including work output, energy efficiency and exergy efficiency were numerically investigated and compared.

2. Working principles of APG cycles and analysis methods

The system schematic and enthalpy-mass fraction (h-w) diagrams of different APG cycles studied in this work are depicted with exemplified operational conditions. The condensation lines and boiling lines of ammonia-water solution were calculated using the equations given by El-Sayed and Tribus [23], while the enthalpies and entropies were calculated based on the Gibbs free energy formulations reported by Ziegler and Trepp [24].

The performance of different APG cycles has been numerically evaluated and compared based on the following assumptions.

- APG cycles were all operated at steady-state.
- The liquid solution at the outlet of condenser was at saturated state.
- Both the vapour and liquid from the separator were at saturated state.
- Throttling process did not change the enthalpy.
- The mixing process in the mixer was an adiabatic process.
- Pressure drop and heat loss in the system were both neglected.

2.1. KCS-11

The absorber in conventional absorption system is replaced by a mixer and a condenser to form the KCS-11 system as shown in Fig. 1. The mixer is to collect and mix the turbine exhaust and the ammonia-lean liquid from the separator, while the condenser locates at the downstream of the mixer. The ammonia-water solution passing through the condenser, pump, recuperator and the boiler is defined as the basic working solution. The condensed basic solution (10–1) is pumped from the condenser to high pressure by a solution pump (1–2) and pre-heated (2–3) by the ammonia-lean fluid from the separator in a recuperator before it enters a boiler. The boiler generates liquid-vapour two phase ammonia-water mixture (3–4) which is then split to saturated ammonia-rich vapour and saturated ammonia-lean liquid by the separator (4–6, 4–5). The vapour expands through the turbine (6–7) with mechanical energy output while the liquid releases its residual heat in the recuperator (5–8) before being throttled (8–9) and mixing with the turbine exhaust in the mixer (7, 9–10).