Energy 87 (2015) 425–434

Contents lists available at ScienceDirect

Energy

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

A comparative study on the ammonia–water based bottoming power cycles: The exergoeconomic viewpoint

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ARTICLE INFO

Article history:
Received 6 September 2014
Received in revised form
5 April 2015
Accepted 1 May 2015
Available online 29 May 2015

Keywords:
Exergy
Exergoeconomics
Rankine cycle
Ammonia–water mixture
Ammonia concentration
Low temperature heat source

ABSTRACT

A comparative exergoeconomic assessment is reported for Ammonia-Water Rankine (AWR) and Ammonia-Water Recuperative Rankine (AWRR) bottoming power cycles. Through investigating temperature distributions of hot and cold fluids and pinch point location in heat exchangers, first energy and exergy analysis is performed and then cost balances and appropriate auxiliary equations are developed for components, so exergoeconomic variables are quantified. A parametric study is also performed to examine the effects on exergoeconomic performance of the cycles, of turbine inlet pressure and ammonia mass fraction in the working fluid. As a result, unit cost of electricity produced by turbine is determined to be 11.87 and 13.85 cent/kWh for the AWR and AWRR systems, respectively. Based on these values it is interesting to note that, unlike the energy and exergy analysis, the exergoeconomic viewpoint prefers the AWR system to AWRR. Also parametric study revealed that ammonia concentration has a great effect on exergoeconomic performance of the both systems. Increasing ammonia mass fraction increases total exergy destruction cost rate as well as unit cost of electricity produced by turbine in the both AWR and AWRR systems. This shows the advantage of using a binary mixture such as ammonia–water as a working fluid in these cycles.

1. Introduction

Increasing the consumption of fossil fuels to satisfy the growing world energy demand leads to increasing concerns about depletion of fossil fuel resources and air pollution. So the interest in efficient methods of energy generation has increased. One of the trustworthy methods is effective use of every power and thermal energy that can be utilized from a fuel source. Thus, in recent years, greater attention has been paid to the utilization of low grade waste heat for electrical power production.

Among the bottoming cycles, Organic Rankine Cycles (ORCs) have several promising features that make them a suitable choice for production of electrical power from low and medium temperature heat sources [1]. At low temperatures, organic fluids cause higher efficiency than water for power cycles [2]. Since pure fluids evaporate and condense at constant temperature, a large temperature difference occurs in the evaporator and condenser of the cycle. This increases the irreversibility and consequently degrades the performance of the system. To improving the performance, using the zeotropic binary mixtures such as ammonia–water as a working fluid is suggested. Heat can be rejected from or supplied to these fluids at constant pressure but at variable temperature. This improves the temperature matching between cold and hot streams in the heat exchangers and reduces the exergy destruction in the power cycle. The use of ammonia with water in a binary mixture has several advantages. For example, existing designs for the steam turbines can still be used in ammonia–water based power cycles since water and ammonia have close values of the molecular weights. Also, the boiling temperature of ammonia is lower than water which improves the performance of the cycle in power producing from a low grade heat source [3].

Changing ammonia concentration in the ammonia–water mixture as a working fluid enables the power cycle to adapt with renewable energy sources fluctuations. Wagar et al. [4] carried out a thermodynamic analysis of an ammonia–water based rankine cycle for power production from the renewable energy resources and industrial waste heat. They reported that the source temperature and ammonia concentration in the mixture dramatically affect the cycle performance. Roy et al. [5] performed a thermodynamic analysis of two ammonia–water based

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http://dx.doi.org/10.1016/j.energy.2015.05.023

Nomenclature

A	heat transfer area (m^2)
c	cost per exergy unit (\$/kJ)
$\dot{C}$	cost rate (\$/s)
ex	specific exergy (kJ/kg)
$\dot{E}x$	exergy rate (kW)
f	exergoeconomic factor
h	specific enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (bar, kPa)
P_H	turbine inlet pressure (bar, kPa)
$\dot{Q}$	heat transfer rate (kW)
s	specific entropy (kJ/kg K)
T	temperature (°C, K)
v	specific volume (m^3/kg)
$\dot{W}$	electrical power (kW)
x	ammonia mass fraction in the working fluid
Z	capital cost of a component (\$)
$\dot{Z}$	capital cost rate (\$/s)

Greek letters

η	energy efficiency, isentropic efficiency
ε	exergy efficiency

Subscripts

1, 2, 3, …	state points
aw	ammonia–water mixture
C	condenser
cw	cooling water
D	destruction
E	evaporator
F	fuel
j	*j*th stream
k	*k*th component
L	loss
P	pump, product
pp	pinch point
q	heat
R	recuperator
s	source
T	turbine
W	power

rankine cycles (one with generator and the other without it) for power production from low temperature energy source considering fixed temperature of source and sink inlet. They found that the applicable range of the evaporation pressure increases with ammonia concentration and source temperature. Kim et al. [3] presented a thermodynamic analysis of Ammonia–Water Rankine (AWR) and Ammonia–Water Recuperative Rankine (AWRR) power cycles and investigated the effects on system performance of ammonia mass concentration in the working fluid. They also examined temperature distributions of streams in the heat exchangers at different concentrations of ammonia in detail. Results showed that the AWRR has higher energy and exergy efficiency compared to AWR. Kim et al. [6] in another paper presented a novel and efficient model to assessment of pinch point in heat exchangers of ammonia–water based power cycles which is more complicated compared to cases with a pure substance working fluid.

Many scientists and engineers believe that the best thermodynamic analysis is performed through exergy [7]. Exergoeconomics is a rather new area of engineering that combines exergy based thermodynamic analysis with economic principles and provides important information that is worthwhile for a cost effective operation of an energy system and cannot be achieved using either thermodynamic or economic assessments, separately [8]. In an exergoeconomic analysis the costs related to thermodynamic inefficiencies are incorporated in the total product costs of the system. These costs reveal the cost formation process in the system [9].

The exergoeconomic concept has been used in recent years to analyze and optimization of energy systems [10–19]. Lee et al. [20] carried out an exergoeconomic analysis for a fuel cell based combined heat and power system. The results showed that the capital costs of fuel cell stack, fuel blower and heat recovery water pump should be reduced since these components have higher exergoeconomic factors. Mohammadkhani et al. [21] performed an exergoeconomic analysis for heat recovery process from a gas turbine modular helium reactor using two organic rankine cycles. Results of the study showed that precooler, intercooler and condensers have the worst exergoeconomic performance. They also carried out a parametric study to investigate the effects on the exergoeconomic performance of the system of important parameters. Ahmadi et al. [22] reported an exergy and exergoenvironmental analysis for a trigeneration system consisting of a gas turbine cycle, an absorption chiller, an organic rankine cycle and a domestic water heater in which the environmental impacts are also taken into consideration. The results revealed that compared to the gas turbine cycles or typical combined heat and power systems, the studied trigeneration system has lower carbon dioxide emissions.

In the present work, an exergoeconomic analysis is performed to Ammonia–Water Rankine (AWR) and Ammonia–Water Recuperative Rankine (AWRR) bottoming power cycles which, to the authors' knowledge, has not been performed yet. For this purpose, the cycles are first investigated through energy and exergy, and pinch point locations as well as temperature distributions of hot and cold streams in heat exchangers are determined. These distributions are compared with Kim et al. [3] results to validate the developed simulation model. In order to detect irreversibility distribution in the cycles, exergy destructions and exergy efficiencies are calculated for components. Then cost balances and auxiliary equations are developed for components and values of the cost rates are calculated for each stream of the cycles. Using these values, exergoeconomic variables are determined and compared for the two cycles. Although the rankine and recuperative rankine are two well-known power cycles, a literature review reveals that there have been no many studies on the ammonia–water based ones and especially on the effects of ammonia concentration on the performance of the cycles. However, some efforts have been reported on the effects on energy and exergy characteristics [3,6,23–25]. As an attempt to fulfill the lack of information about the effects on exergoeconomic performance, finally a comprehensive parametric study is carried out to identify the effects of ammonia concentration as well as turbine inlet pressure on exergoeconomic performance of the cycles.